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Review of grid-tie micro-generation systems without energy storage: Towards a new approach to sustainable hybrid energy systems linked to energy efficiency

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ABSTRACT

This paper reviews the literature on the subject albeit approaching hybrid micro-generation power systems from a systems thinking (ST) and cybernetics standpoint, viewing them as dynamically complex adaptive systems (CAS) coupled with and supplying to a set of homes termed a sustainable block in a rural setting. Here homeostatic regulation (HR) and control play a vital role in reaching efficient equilibrium towards reconciling power supply and demand response management. Unlike most of the work reviewed in the literature, the focus here is on supervisory control of grid-connected micro-generation systems without energy storage, aiming towards building energy efficiency, thriftiness and sustainability in energy consumption. Building on homeostatic control (HC) principles first introduced by F.C. Schweppe in 1979, the paper explores the concepts of sustainability and sustainable hybrid energy systems (SHES) applied to micro-generation, focusing on operational aspects rather than on socio-economic, environmental or regulatory ones. A concrete theoretical model for building a SHES is presented for a proposed grid-connected renewable microgrid. The model seeks to reconcile power supply and demand towards efficient equilibrium (homeostasis) proposing reward-based criteria for controlling renewable electricity supply and consumption in rural communities in Chile. Discussion and recommendations are also offered stating that energy sustainability (ES) is essentially a systems issue, and one where ES is first and foremost a structural, organizational and operational property which is in the very nature of the system itself – it is built into it – rather than explained by exogenous factors.

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1. Introduction

The potential for using hybrid renewable energy systems (HRES) based on non-conventional renewable energies (NCRE) for electricity generation in rural and remote communities is big and growing and Chile is a perfect candidate for such initiatives being rich in renewable energy sources (RES) throughout its long territory. For this purpose drivers for implementing distributed generation (DG) systems using NCRE are to be identified in each case, but in general, these are the geographic potentials for production, the technology available and the social, economic and political support garnered along with the active involvement of the local community and authorities, respectively [1–33]. Therefore, to meet the energy requirements of remote and rural communities, HRES for DG of electricity and heat – working in a variety of smart microgrid configurations – can be a viable and convenient solution, especially in those places where there is still no electrical energy distribution network available as it is presently the case in many locations of Latin America. However the cost of hybrid energy systems based on renewable energy technologies (RET) is generally high and there is also the problem of reliability associated with the RET due to the intermittent nature of RES [1–8]. Thus there arises the need to design and develop small, modular, smarter hybrid micro-generation systems (HMS) that are efficient, cost-effective and economically profitable as an investment notwithstanding their small size and power generation ranges, which usually operate in the kW range. They are employed for residential or small commercial/industrial purposes and also for small size power back-up applications, rather than in the mega watt (MW) range for power utility size applications. These can be comprised of mature technologies such as small wind turbines, photovoltaic (PV) panels and microturbines or generators, for example, operating on diesel or with liquefied petroleum gas (LPG), in rural/remote locations which can also incorporate different options of energy storage systems (ESS) [9,10] but only when these are economically feasible for the project's users, are deemed appropriate and necessary for the particular configuration and sizing chosen for specific needs, and are not thwarted by the location's ordinances, environmental or budget restrictions, many of which exist today in several locations of Chile as well as in the rest of the world. With respect to this, the examination of past energy technology practices at other well known sites with uniquely fragile environment [6–8,12–33,129] can provide valuable lessons for new HRES designs that integrate centralized power generation and distribution infrastructure with local RES, matching distributed energy demand with local power supply effectively [1–8]. Likewise NCRE have significant potential for contributing to the economic, social and environmental sustainability of these rural and remote communities, which are so abundant in number in South America. They also reduce emissions of local and global pollutants and may create local socioeconomic development opportunities as well [1–33]. On the other hand, sustainable hybrid energy systems (SHES) are those that can overcome perturbations and chaos, enduring adverse and changing conditions in spite of how complex the environment in which they are immersed turns out to be. Chaos theory studies the behavior of complex, dynamical systems that are capable of adapting and are highly sensitive to initial conditions [226,227] just like HRES are. Such systems face unpredictable conditions and situations continuously, throughout their operation, due to a myriad of factors, such as the weather, sudden and abrupt changes in peak power demand and harmonics, for example. Maintaining voltage and frequency stability is also a concern – especially when operating in tandem and parallel with the grid – indeed a complex ongoing task for such systems [93–108]. Small differences in initial conditions or in operating parameters which directly determine their generating capacity and the quality of their power supply at any point in time can yield widely diverging outcomes in HRES. This is particularly true for HRES connected to the grid and operating without energy storage systems (ESS). Up until now, much work has been published on stand-alone and grid-connected HRES with energy storage [1–183,187–208], yet upon an extensive review of the relevant literature on the subject, it is found that there is a void in this area in particular, with practically no research work published on grid-connected HRES without energy storage. Therefore there is a clear need to address such systems configuration and device new and innovative supervisory control strategies [30–34] from an alternative viewpoint that can aid more effectively and efficiently in the coordination and control of such systems operation, equipping them with the means to overcome these challenges. Moreover, these new and innovative supervisory control strategies for MGS – especially for those tied to the grid – must be addressed and resolved but with customers (loads) being active players in such strategies, not passive ones as seen in several other more traditional approaches to the subject, which focus rather on components, technology choices and in energy management devices that totally exclude or bypass the energy user interaction and choice. For this task several approaches were reviewed in the literature, where the hybrid micro-generation plant generally has some type of device incorporated in its control system which decides when, how and how much to adjust the power supply and manage energy demand response in order to carry out load shedding, in an effort to keep the system's stability in regards to power supply and demand side management (DSM) requirements. This is particularly complex with respect to reconciling power supply and energy demand management in grid-connected micro-generation power systems operating without energy storage, where the price of electricity supplied by the local grid can be very high at certain times of day and during seasons of high energy demand like in several touristic locations throughout Chile, particularly so in the south and north of the country and in places like Easter Island or the large island of Chiloe, located at the far south tip of Chile. Therefore it is in this particular case where there is a need – addressed in this paper –

that has not yet been adequately met, to propose new strategies for meeting this challenge and for devising more sustainable hybrid energy strategies to advance in the direction of DG's integration to the grid with a variety of renewable MGS employing diverse RES, thus harnessing the current electric power infrastructure to make such hybrid MGS more stable and secure in the absence of energy storage devices. The utility grid, in the case of Chile, is very much present everywhere yet at an onerous price and subject to instability due to load fluctuations and limited capacity, along with frequent difficult weather conditions (strong winds, heavy rain and snow) and quakes. This is something that has the government authorities worried considering the fragile power infrastructure of the country in light of such natural events and the high price of electricity paid in Chile – the highest in the region – and especially expensive in the central and southern parts of the country. Thus, the days of huge, highly centralized and rigid electric power networks paradigm may be numbered based on the current trends in the electric power generation and distribution industries worldwide [1–171]. Yet, despite the vulnerability that such systems entail based on the issues already discussed, right along with the dire need to reduce high energy costs and become more efficient and energy sustainable in offering electrical energy and heating services to the population, little has been done about it in Chile as of today, and less has been achieved despite the important academic and research contributions [227,232–243]. Especially so in regards to advancing the country's energy efficiency (EE) [243] and the DG agenda, wisely integrating NCRE to the traditional hydroelectric and fossil fuels-based power generation infrastructure and thus moving towards a more decentralized, flexible and sustainable energy system infrastructure for the entire country, one that is more in tune with the current needs and realities of today's energy and economic scenario.

1.1. Homeostasis as metabolic mechanism of living life forms

Homeostasis refers to stability, balance of metabolic processes in humans and animals. Maintaining a stable body system is essential for sustainability of living systems. It requires constant monitoring and adjustments by means of efficient and effective feedback loops-based control in the body as conditions change. Just like the constant process of adjustment of physiological systems within the body, constantly working to adapt the system to new and changing conditions. Such mechanism is called homeostatic regulation (HR), and involves three elements: (1) the receptor, (2) the control center and (3) the effector. Metabolism being a vital process for all life forms – not just humans and animals – is a collection of chemical reactions that takes place in the organism's cells. Metabolism in living systems is a dynamically complex, adaptive process which is also a constant, continuous and life-long process. If the metabolism of the living system stops, the system dies.

Sustainability, on the other hand, is the capacity of living systems to endure and survive, overcoming adverse conditions in spite of the changes that may occur within or outside of the system. It is a characteristic which is inherent to all living systems, whether open or closed. All living systems are determined by their structure and organization and such is the case with the HRES, when it is connected to the grid and supplying power to a group of homes without energy storage. In fact, upon examining the system closely from a systemic and cybernetics standpoint, one finds that it is no different from other living systems when the customers/users of the system are part of it and a crucial one of the entire meta-system, when viewed as a dynamically complex, adaptive socio-technical system [119]. Thus the development of HRES as SHES is evidently important and necessary for building the smart, robust and efficient micro-generation systems of the future, especially when it comes to the smart HRES as a microgrid [1–171]. However, unlike most of the work done up to the present day on the subject of sustainability and sustainable energy systems, which mainly addresses economic, environmental, social and regulatory issues, the present work detours from such path and focuses rather on the concept of *built-in sustainability* in such energy systems. Thus, departing from main stream analysis of sustainability in micro-generation power systems in particular, the paper builds on homeostatic control (HC) principles and concepts [177–183] employing a systems thinking (ST) and cybernetics [212–224] approach and explores the operational and systemic aspects of such systems when viewed as CAS in regards to reconciling power supply and energy demand response management towards an efficient equilibrium (homeostasis), offering a novel approach to reconcile energy supply and consumption which can help build more sustainable hybrid micro-generation systems (HMS) (Fig. 1).

1.2. Building sustainability in hybrid micro-generation systems (HMS)

It is found that the literature dealing with the subject addresses the classical issues on sustainability in a way that somehow overlooks the more technical and operational aspects of sustainable hybrid energy systems (SHES). Often times making the social, economic and environmental dimensions of energy supply and consumption management the key issues in decision making, going as far as suggesting that there is a need for an energy ethics—a moral obligation to deal with the energy problems that are at the center of that decision making process [172–174]. Sustainable energy practices and technologies are no doubt important in today's age but they are not a “moral obligation”

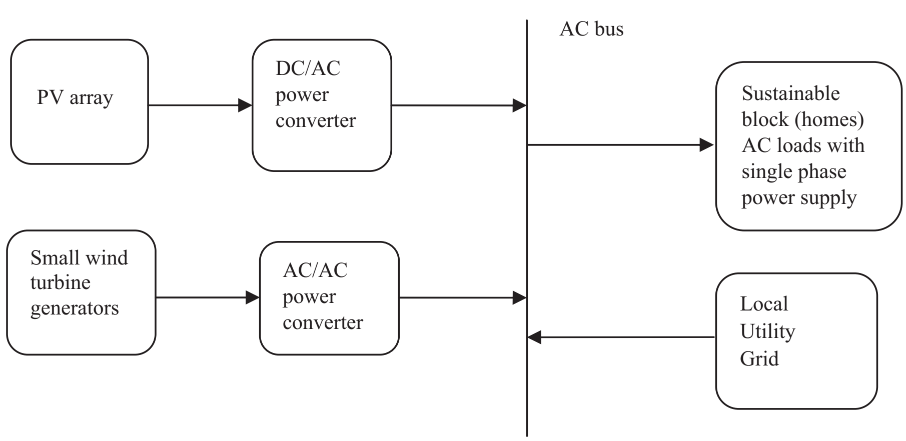

Fig. 1. Schematic diagram of a grid-connected PV-wind HRES without energy storage to supply power to a sustainable block in a rural community. Smart metering and supervisory control employing HC principles and especial features customized for consumers are also considered in the specific design.

to be kept as a beacon for safeguarding the world's energy future. Sustainability is first and foremost both a technical and an operational issue; it is complex and systemic in nature, meaning that an energy systems engineering approach must be adopted, especially at the decision making stages regarding system design and planning, encompassing several factors that are within the scope of sustainable energy systems. Other authors address system sustainability differently, focusing on policy and regulations, presenting ethical challenges that require an inclusive and holistic approach that transcends traditional decision-making mind frames [3–80,84–160]. Unlike other approaches already explored at length in the literature, this paper does not pretend to approach the *energy dilemma* from the broader perspective of sustainability, discussed in several papers [3–80,84–160] but rather from a narrower and more concise one, focusing on homeostasis as an enabling mechanism towards efficient equilibrium in such systems. Rather than aiming to preserve the world for future generations through the use of new sustainable energy models, applied to microgrids, looking mostly at the sources of energy and their management, based on socio-economic, technical and environmental factors and their inherent sustainability within an adequate regulatory framework of the site, this paper focuses on the nature of sustainability itself in such a system. Mainstream views, particularly in Chile where there is a strong group of green activists and environmentalists ready to strike and make their voice heard, halting large conventional hydroelectric and fossil fuel projects because of socio-cultural and environmental concerns, and favoring "green energy" derived from RES to be used everywhere 100% whenever possible. Yet this is not always possible or adequate, given the circumstances and conditions of so many different rural locations around the world; particularly in Chile where the grid is almost always present, yet at a high cost. Thus a proper combination of RES-based technologies and conventional energy sources is used in such cases, along with proper systems dimensioning, components sizing and load management (demand for energy, as well as how and when it is expended).

Likewise, it is expected that by 2020 there will be a restriction in energy supply from fossil fuels due to a complex mix of socio-economic forces, along with environmental, regulatory and hydrocarbons supply factors. In this context several developed countries and some developing countries such as Chile – a current member of the OECD – have sought to face the challenge by addressing the problem in its root-cause: an excessive use of fossil fuels in the country's energy generation matrix, with a heavily concentrated industry and inadequate legislation that thwarts the growth of DG and hinders the integration of NCRE in the current state of the electricity industrial sector of the country. By law, renewables must represent 10% of the country's energy matrix by 2024. Notwithstanding the various and diverse considerations and opinions regarding the initiative, what is true and relevant to this work is that Chile in particular has sought to face this pressing issue by taking up certain goals, such as 20/20 yardstick, meaning that 20% of the energy supply matrix shall come from renewable energy by the year 2020, in order to significantly increase the participation of NCRE in the electricity generation and distribution sectors. As a matter of fact, at present there is not practically any significant share of renewables in the Chilean energy matrix. Currently NCRE only amount to 3% of the total, something that for Chile's strong RES and dire energy needs is perplexing. Hence Chile wants to bring about a significant change in the coming years towards a greener, more diversified, flexible and sustainable energy matrix; one which hopefully will be much less concentrated and single-sided than the present state of the electric sector.

However, there are still important obstacles ahead that can hinder the advancement of such commending endeavor. During the next decade and towards 2035, it is expected that NCRE will play a much bigger role in world's energy supply and looking towards 2025 an increasingly important role in Chile's economic development. Particularly advancements in DG and HRES integration have been primarily thwarted by the lack of adequate legislation that allows and incentivizes DG penetration in the country's current energy matrix; but also due to the identification of many complexities, including efficiently matching supply and demand. The is also a need to consider the scale of current and projected needs, and the many difficulties associated with replacing the presently highly centralized, unidirectional electric power system with far more flexible yet complex decentralized power systems (DPS) in the form of smart HRES with microgrid technology. Such systems utilize different and dispersed energy sources as well as energy supplies for which new, more flexible and effective coordination and control strategies will be needed. Thus, a major challenge that stands up above and beyond the legislation hurdle today is the need to design new, more flexible, efficient and smarter systems that can leverage existing power infrastructure, based on the current centralized generation and distribution scheme, to take advantage of alternative sources at the local level and more so at remote, isolated locations, especially in a long and heterogeneous country like Chile (Table 1).

On the other hand, identifying and reaching out to key enablers – whether these are people in key positions or organizations and local governmental authorities – is a vital task in order to rally people for the cause of advancing the use of NCRE and the development and integration of DG systems and technologies. In order to integrate alternative/NCRE in places like rural communities and in small islands (Chile has a great number of these as part of its territory), it is necessary to engage leaders to work in favor of stirring public awareness of the issue. The case must be made for leadership to act on the need towards decentralization of electric power generation and distribution infrastructure in Chile, to unlock the gridlock currently in place which hinders and prevents DG and decentralized power systems (DPS) to flourish. It is therefore crucial, particularly with regards to HRES and microgrid projects [1–162] through the integration of NCRE employing smart microgrid technologies [163–172] reviewed here, to reach out to influential and passionate leaders and institutions such as research and development funding organizations like CONICYT[3] as well as other public and private organizations that can rally support and provide necessary funding for research and development in this important field.

The paper is divided into four sections, with Section 1 offering some background on the relevant subjects, plus the contextual motivation on the need to advance DG and the decentralization of electric power systems worldwide and taking Chile as a particular example of this pressing need. Such a need exists today both at the generation and distribution levels in Chile and can certainly be addressed and resolved with the right incentives and an adequate regulatory framework from the government. It can be realized through the implementation of both stand-alone and grid-connected hybrid electric power systems (HEPS) employing NCRE and conventional energy sources like microturbines and mini hydro in Chile, a country where there are many run-of-river opportunities awaiting to be taken all through the central and south regions of its territory for such technology. Likewise, there are technologies that can aid and complement well this trend in the use of smart microgrid technologies for differentiated energy sources such as smart metering and differentiated energy pricing [57,67,140] through flexible demand management for example, just like it is done in the residential home heating sector with natural gas today in many places. A complete literature review on the relevant issues is also presented in this and in the next section

[3] Comisión Nacional de Investigación Científica y Tecnológica, Gobierno de Chile, CONICYT.

Table 1
Centralized, hierarchical and conventional electric power systems characteristics versus decentralized, flexible and more sustainable power systems.

Electric power system type	Centralized power systems	Decentralized power systems
Overall system's characteristics and traits	Little flexibility and adaptability if any. Hierarchically structured, robust configurations with a central supervisory control agent; remote agents with limited capabilities. System is highly dependent on central control and grid operator for all decision-making and this makes it slow and impractical/less able for systems fluctuations and natural disaster-response preparedness	There is no central supervisory control agent. There are several distributed generation (DG) and power distribution agents dispersed, feeding a series of diverse AC loads along multiple buses. Agents are organized in very nimble and flexible yet robust configurations, with sophisticated communication systems. There are ample measures and means of redundancy in communication and control and they all make decisions collectively and systemically
Communication systems configuration and Infrastructure characteristics	Usually use client-server communications albeit with limited communication paths. Main reason behind this is increased efficiency and focus. Aim at decreased risk of technological clash by providing oversight to ensure software and hardware are both compatible within the general system architecture	Having as many communication paths as it is necessary. Network is extended as needed, using all technological means available, securing robust yet agile and flexible communication systems integration. Compatibility issues among different units should be watched for, along with lack of oversight and long term systems planning coherence. Compatibility is key factor to ensuring overall system's dependability, seamless functionality and readiness within the entire system. Customer choices are important
Control systems type and overall synchronization strategy characteristics	Hierarchical central supervisory control system sets the norm and standards, all under one umbrella; all control actions are monitored and are dependent on central controller control is based on serial configuration, highly inflexible and subject to single-node failure	Multiple agents comprise the entire system, distributed control systems architecture. All agents act independently; communications and control actions occur asynchronously and in parallel. Redundancy through different networking mesh must be ensured and star type of linkage is preferred to avoid single-node failures. Aim is on super fast, reliable and agile control actions
Integration characteristics	In order to enter or to exit the electric power system infrastructure, all actions and standards to access the system are dictated by and coordinated with the supervisory controller	Very flexible, seamless, fast and easily deployable, flexible implementation and ready to install and run operation ("plug & play" configuration) Overall integration strategy facilitates that various agents can enter and leave the system as needed or as conditions allow
Overall systems sustainability	System control scheme with little sustainability index. Usually it is totally dependent on central supervisory control unit and prone to system's structural weaknesses	High system dependability; control responsibilities are highly distributed and balanced among the different agents. Never dependent on a single node and thus not subjected to structural weaknesses. Interaction among systems and smart, fast and secure event response management and control are indispensable requirements
Overall systems reliability/ dependability	Good under normal, standard conditions. Low or no resilience capacity to sudden strong climatic perturbations and unpredictable cascaded failure typical of those provoked by natural disasters, technical/maintenance issues, vandalism or by terrorists acts. Low reliability due to Single-node of failure; central supervisor must be redundant	High, decision-making scheme is multi-sourced, very reliable and flexible, and should never be dependent on a single node. Watch for overly expensive configuration schemes and excessive sophistication as it may be a problem in the medium-to-long-term due to cost and technical issues

as well. Section 2 presents the general theoretical framework supporting the approach chosen, based on homeostasis and homeostatic control (HC) and briefly reviews the concept of self-regulating, self-organizing, evolving complex adaptive systems. Section 3 presents the theoretical model and gives an example of the criteria employed, along with a brief discussion. A novel coordination and control strategy for the supervisory control of HRES power supply is proposed based on such criteria. Also to illustrate the latter, a sample criterion is presented as an example, aimed at managing the power supply and residential energy consumption of a small rural community, typical of many such communities in Chile and other neighboring countries. The analysis carried out therein is intended to understand HRES for electric power supply to small and rural communities much like living organisms that are subject to homeostatic regulation (HR) when built in a smart microgrid arrangement, operating grid-connected but without energy storage. Such HRES can very well operate in parallel to the grid and be a much more economical alternative for consumers, supplying electricity to a group of homes termed a sustainable block. Thus in the context of the present work it is argued that, when it comes to adaptive load management mechanisms like demand response management to reach a more effective energy supply and demand equilibrium in such communities, a complex adaptive system (CAS), systems thinking (ST) and cybernetics viewpoint [212–224] may be employed. A sustainable block is, before anything else, a dynamical socio-technical system which behaves much like a CAS, a living system. As such, it is capable of having well defined characteristics and properties inherent to such systems and therefore, through emergence and co-evolution, it can display self-organizing and adaptative behavior capabilities, thus behaving as intelligent open systems when interacting with other higher-order systems such as the utility grid and the energy consumers in their homes. The three are capable of comprising a sustainable hybrid energy system (SHES) – a meta-system – that can develop greater degrees of energy sustainability and autonomy as the technology, along with the supervisory control strategy further develop and mature overtime. Likewise, some useful insight on its operation and potential technological schemes to implement such technology are shown. Finally in Sections 4 and 5, a recap of the main theoretical framework elements is presented along with the model highlights supporting the present approach, offering concluding remarks, plus a view of what future perspectives that research work in the field may bring.

1.3. Reviewing the relevant issues in distributed generation (DG) and hybrid renewable energy systems (HRES)

In regards to HRES implementation in particular, the cost of photovoltaic and/or wind power generation lays in the form of upfront capital expenditures, where the average cost instead of marginal cost is what is relevant; yet the operation and maintenance expenses in these systems are generally quite low when

compared to conventional power machinery. Therefore, the generating cost via photovoltaic or wind or both is marginally more than a conventional system with respect to the additional generating capacity, and depending on the size and particular configuration it can run very high in price compared to diesel generators [1–34]. Nevertheless it promises customer satisfaction of a clean, continuous and cheap electricity and heat supply if consumption is kept within moderate ranges. For those consumers that wish to use much more energy on a regular basis than those situated on the average monthly energy consumption, they can always get it from the grid albeit at a price that in rural and remote locations can be much higher than the already expensive price paid in the metropolitan region of Chile as an example. The paper “Bibliometric analysis of distributed generation” [24] covers the DG topic extensively, and defines it as a generation source that is connected to the distribution system close to the load. DG encompasses both renewable and non-renewable sources in whatever sizing and configuration chosen. The authors highlight the main directions within the power engineering research community in the field of DG, signaling microgrids and smart grids as the most prominent trend in their review and the need to efficiently integrate DG to the grid. They point out that such trend can be seen as increasing rapidly after the year 2000 [24] and especially in the last seven years with well defined areas of development. Also revealing was that for 7 out of the 10 topics, the inverter-based interface technology had the highest rate of growth, signaling that grid-connected HRES is a priority. Focusing on future trends for design and operation of HRES [24], considerations for a system designed on two modes are discussed. One is stand-alone and other is grid-assisted mode. In stand-alone mode, it draws power from the wind–solar hybrid energy system. In the grid-assisted mode, when the HRES is unable to feed the power, it automatically takes the grid power. However the discussion is centered on components and technical characteristics considerations only. Nothing is said in regards to how interconnected systems can coordinate with and assist each other and work together as a collective to face changing scenarios and varying degrees of complexity, looking for ways in which they are better able and suited to regulate themselves and adapt to changing conditions as needed to make the entire meta-system successful.

In *“A current and future state-of-the-art development of hybrid energy system using wind and PV solar: a review”* [27], the authors define a hybrid renewable energy system (HRES) as one consisting of two or more energy sources, a power conditioning equipment, a controller and an optional energy storage system [27], if the site's norms and regulations allow such resource. Authors review the current state of the arte operation and control requirements of stand-alone PV solar–wind hybrid energy systems with conventional backup source. Their review reveals that HRES are not cost competitive against conventional fossil fuel power systems, yet there is good perspective that such systems will be introduced more widely in the near future in the rural households of developed and developing countries like Chile, that attach high value to a reliable, limited supply of clean electricity linked to low carbon emissions and EE [27]. HRES are also important as a viable option power supply for community facilities [27] both as an alternative and a complement to the grid supply. Hence community facilities such as rural hospitals, schools, telecommunication stations, distributed heating and water pumping units can contribute significantly to the welfare and sustainability of rural and remote communities everywhere, especially in underdeveloped and developing nations where there is still much to be done. They add further that research and development efforts in solar, wind, and other renewable energy technologies (RETs) are required to continue improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources [27]. It has also been demonstrated that hybrid energy systems can significantly reduce the total lifecycle cost of standalone power supplies in many situations, while at the same time, providing a more reliable supply of electricity through the combination of energy sources [27]. The controller and power conditioning units are used to maintain the grid quality power [27–34]. Park et al. [33] presented the power compensation system for controlling energy flow through hybrid energy system according to load demand. Valenciaga and Puleston [34] researching on supervisory control for a stand-alone HRES developed three modes of operation and they used sliding mode control methods. In the configuration proposed for the conventional system's components, point out that either diesel generators or the utility grid may be used as back-up power supply [34]. Yet again, nothing is said of systems interaction, self-regulating, organizing capacity, adapting themselves as a collective and working together in coordinated manner, assisting themselves to be more operationally efficient and effective including the customers in their homes in the sustainable block in order to achieve their goal. There is also found in the literature a poor treatment of the communication among the systems and subsystems comprising a smart microgrid in which HRES operate, and what can be achieved by this, limiting barely to the treatment of technical aspects of communication systems and control links present in the HRES. Another interesting paper reviewed is *“A methodology for community engagement in the introduction of renewable based smart microgrid”* [35], where Rodrigo Palma and his group devised a methodology for the technology appraisal of local scale introduction of new technologies based on smart microgrids and RES. A methodology of community intervention for the introduction of a smart microgrid system in a rural community is proposed to adequately manage the introduction of new energy technologies in a rural setting and the challenges that this may pose, since it generates changes in patterns of energy consumption and habits that affect the demand of the system [34,35]. Smart microgrids have the advantage of being more resilient than conventional approaches to renewable energy, as they can adapt to changes in the demand and through time. The proposed methodology is based on the concept of a community as a socio-ecological system approach affected by a technological intervention, aimed to move towards a stage of more sustainable use of renewable resources [1–162].

The paper *“Distributed energy resources and benefits to the environment”* [36] gives a detailed overview of distributed energy technologies (DET) in use today while discussing the devastating impacts of the conventional power plants feeding on fossil fuels to our environment. The paper finds that such DET generation that feed on RES would not only help meet the growing energy demand – especially in developing countries like Chile which faces a complicated outlook in the years ahead – but also preserve the environment from the devastating effects of fossil fuels in our air and climate [37,38]. Authors point out that HRES of various capacities and configurations have been utilized in developing countries where the rapid growth of load demand undermines grid reliability and the farther the distance, the more expensive the electricity gets [34,35]. Chile is a good example of this, especially in some fast-growing rural areas of the country where climate is very important for the local economy. In this regard, the studies in [27–36] justify the premise that DG technologies could substantially reduce impact of fossil fuels on climate change. An interesting figure is shown with historical and projected world energy demand by fuels. The paper *“Optimised model for community-based hybrid energy system”* [38] ascertains that HRES are an excellent solution for electrification in remote/rural areas where the grid extension is difficult and uneconomical. Such systems incorporate a combination of one or several RES and may have conventional diesel generators or the local grid for backup. This paper discusses different

system components of hybrid energy system and develops a general model to find an optimal combination of energy components for a typical rural community minimizing the life cycle cost. A general optimization model for finding an optimal combination of community-based HRES is developed for the Indian DG context. This compatible model is applicable to renewable power generation in any rural village [38].

In *"Distributed multi-generation: a comprehensive view"* [39] authors ascertain that DG has emerged as a key option for promoting EE and thriftiness in the use of RES-based microgrids, as an alternative to traditional power generation. The distributed multi-generation (DMG) systems concept entails the application of various small-scale local multi-generation solutions providing the user with enhanced energy and environmental performance, higher quality of energy services and, in terms of the economic optimization of systems operations, the possibility of flexibly running the plant according to the variable prices of gas, electricity and of other energy-related commodities [39,40–51]. The DGM concept is analyzed offering insight on approaches to energy planning currently available, with DMG framework and characteristics being reviewed along with a summary of the relevant DMG structures. Interestingly authors predict that the trend towards distributed micro-generation systems could be significant in terms of increasing the local energy source availability, reducing both the energy dependency and the vulnerability of the electrical power system from the effects of grid congestions, reducing service interruptions, blackouts, vandalism or natural events. Another threat to consider here is the danger that external attacks on the power infrastructure present, which can be perpetrated by anarchist groups and violent activists out on the streets who take it on the public infrastructure such as the grid aiming their rage towards collective disruptions and chaos. Unfortunately such a threat is prevalent, quite active and menacing today in Chile on certain dates of the year and upon reacting to social demands that are beyond the country's means or simply do not agree with the public policies and current legislation on certain "high pitch" issues like the students plea for free education at all levels, which have high visibility. Hence building more adaptive, self-healing and flexible DG energy systems will no doubt help not only in supplying higher quality, more flexible and versatile energy to consumers everywhere, especially where there is already a power distribution grid. It will also bring better grid operation reliability and dependability and with it, a decrease in power system vulnerability. This holds true especially for Chile, a country with frequent quakes and sometimes unpredictable weather conditions, which in addition to the other threats already mentioned, can undermine the current power infrastructure which is unfortunately all above ground making it extremely vulnerable [208–211] (Fig. 2).

Above a simple feedback model is shown depicting the main agents involved in the problem of reconciling power supply and energy demand response management in a renewable grid-connected microgrid without energy storage devices. The diagram shows systems relations and their interconnecting structure, allowing us to enhance systemic analysis of the meta-system as a whole. The underlying structure hopefully helps to understand better the systemic view behind the proposed control and coordination strategy for such systems. The strategy proposed seeks to influence, motivate and condition consumer behavior towards more efficient, thrifty energy consumption patterns, in line with an efficient power supply by the Microgrid with respect to the grid supply. This in an effort to bring electric power consumption ranges to desired levels within every home of the sustainable block, thus allowing a collective benefits in spite of differentiated levels of energy consumption among consumers, as it is natural that not everyone consumes the same and at the same time. In general when it comes to managing energy production and supply, as well as energy demand and consumption towards a sustainable, efficient equilibrium between the two – particularly with regard to HMS like the smart microgrid concept analyzed – it is helpful to employ a ST and cybernetics [212–224] approach to the subject, looking at these interconnected/coupled systems as complex adaptive systems (CAS) [226–230].

1.4. Why are important communication systems and data-sensing devices for energy supply and consumption in the coordination and control of SHES?

The distinctive feature of an appropriately designed grid control is that it admits local and changing communication networks, is robust with respect to intermittency and latency of its feedback, and also tolerates connection and disconnection of network components such as the "plug-and-play" elements which comprise the modern microgrid reviewed in the literature. In *"A study for optimizing the management strategies of a hybrid photovoltaic-diesel power generation system"* [48], the paper stresses the need for suitable control of interaction among different devices in operation and the grid. The optimal management of a power system consisting of generators fed by alternative energy sources lies in maximizing the resource availability, which is precisely the aim

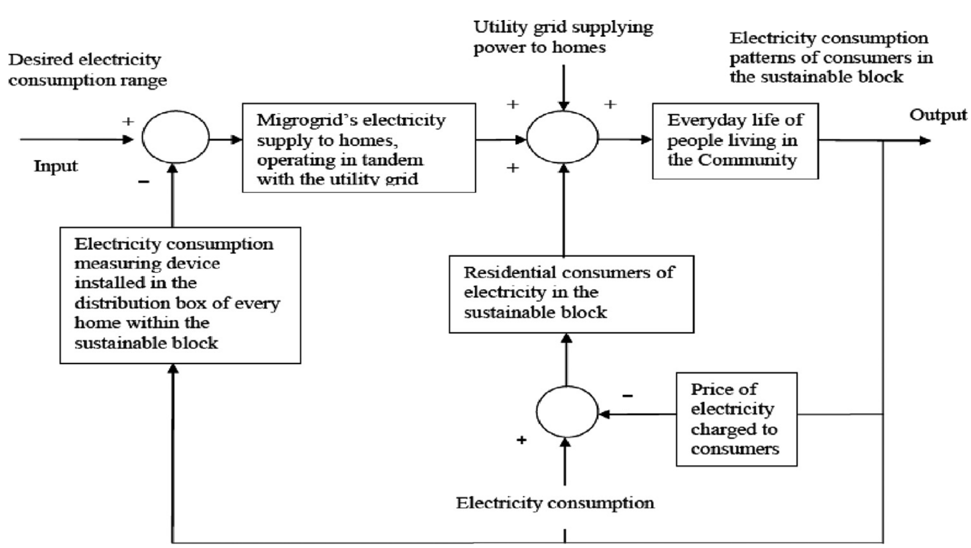

Fig. 2. The role of thriftiness, energy efficiency (EE) and the efficient equilibrium (homeostasis) between energy supply and demand in grid-tie hybrid renewable energy systems (HRES).

behind flexible demand of energy and demand response management. It is also at the heart of the SHES concept being proposed in the present paper. Yet we would add to this that just as important as maximizing renewable resources availability and overall systems capacity, as well as component integration and compatibility, it is also important to analyze how the systems and sub-systems can communicate with each other and how they can share information in real time, thus working collectively and fluidly as a smart meta-system, capable of coordinating and assisting one another in a harmonious manner to reach better results as a whole – a meta-system – rather than as individual systems acting separately. In the paper *"Active and reactive power control and quality management in DG-grid interfaced systems"* [49], the authors state that the main objective of a DG system connected with the utility grid is to control the power that the inverter injects into the grid. According to the grid demand, the controller also injects the reactive power as needed. DG encompasses a wide range of so-called prime movers [49] such as internal combustion (IC) engines, gas turbines, microturbines, photovoltaic (PV), fuel cells and wind-power [49]. These distributed generators are characterized by a low nominal power rating (less than 1 MW). The integrated DG along with grid system can solve many typical problems of conventional AC network such as energy security; reduce transmission and high voltage equipment cost, etc. However, small DG systems employing RES have sometimes significant problems maintaining frequency and voltage stability, both of which can vary substantially when the HRES is operated in stand-alone mode. Therefore, according to the authors, a small DG system should be interconnected with the power distribution grid in order to maintain the frequency and the voltage [49] stability. Also DG-grid interfaced systems with power electronics help improve the power quality problems at point of common coupling (PCC)[4] [49]. Along the same line, the paper *"An integrated hybrid power system based on renewable energy sources with electric wind MPPT"* [50] presents the integration of various renewable sources (wind and solar) with their characteristic stochastic behavior in a HRES. The goal is to analyze the improvement of power quality and economic value of stochastic renewable sources. Within this work context, the renewable sources have continuous maximum power extraction and the two level power management employed is based on energy storage and loading trough a grid-connected inverter [50]. When it comes to DG and the issues related to grid integration, papers by Pepermans et al. [51] and Coster et al. [52] analyze the subject in depth, warning that DG units are most likely to affect the system frequency and voltage as they are often not equipped with a load-frequency control. Thus Ackermann et al. [53] and other authors argue that DG systems will practically "free ride" on the efforts of the electric power transmission network and adapt to the local electric distribution grid's frequency through the inverter [1–8,46–67, 93–108]. Since the grid is the robust, stable, higher-order system which lends its organization, structure and control scheme to the lower-order DG system, essentially incorporating distributed generators like the HRES to its operation and control platform. Therefore, especial care should be taken when connecting a large number of DG units to the grid, carefully evaluating the systems components and their integration to the grid. Also a caveat is mentioned regarding voltage stability, where especially rising voltage levels are observed in radial distribution systems constituting one of the main technical connection issues of DG systems. This however may not be a problem in systems facing low voltage difficulties. In such case DG penetration can have a healing effect on the system voltage profile, but in a microgrid where there are usually weak loads there might be an unwanted voltage increase in the system [51,52]. Again, another reason to explore new ways of applying supervisory control strategies such as those proposed in the current paper to aid in the management and resolution of such problems with flexible energy demand via the right incentives.

Also relevant is the paper *"Grid-connected photovoltaic power systems technical and potential problems—a review"* [54] explains that the increase in demand variability created by intermittent RES such as photovoltaic (PV) and wind presents new challenges to hybrid electric power systems flexibility and adaptability, particularly with respect to energy demand response management [54]. This paper aims to investigate and emphasize the importance of the grid-connected PV system regarding the intermittent nature of renewable generation, and the characterization of PV generation with regard to grid code compliance. Authors address the effect of high PV penetration levels and islanding prevention methods of grid-tie PV microgrids. To meet technical requirements in this case, the DG units in the microgrid must have protection, control and communication components to have a safe operation, yet no customer interface or interaction with the HRES is mentioned other than adding that in order to have flexible planning and operation of distribution system, new methods are required and an intelligent system controller must be used for control and operation of the DG system. This is especially true as already discussed when the microgrid consists of several DG units operating in parallel [54].

On a different arena altogether although a quite interesting one, Agüero et al. in "Energy management based on productiveness concept" [55] introduce the *productiveness concept* in order to manage local energy resources through smart loads. According to this concept a unit of energy (kW h) is 100% productive when applied to maintain the conditions defined in settings and timing established for the user [55]. Hence the final user is willing to pay a price per each kW h consumed in order to maintain the desired comfort conditions. The assumption that electricity demand is almost completely inelastic is changing as a result of deregulated wholesale markets [55]. Productiveness as defined in this paper is a means of meeting two objectives: cost and quality for a group of loads with renewable penetration and/or real-time prices [55]. Authors point out that the main indicator of balance or equilibrium between energy production and demand is the frequency parameter of the load, therefore strategies are proposed to adjust the load to its fluctuations [55,56–89]. In light of this, Ning and Hammerstrom [56] introduce the term "GridFriendly™" [56] loads, indicating that such loads offer an increase in renewable resources by contributing to the primary control of the frequency of the system [56]. Such concept involves grid-connected renewable energy systems where adjusted consumption of renewable energies is imposed by the needs of the grid but not by the individual users. Other authors [53,56–89] have approached the problem of domestic loads management differentiating between critical and controllable, where users can optimize their consumption according to their needs and their local renewable energy production, thanks to the flexibility of their consumption [53,56–89]. Flexibility of demand may be analyzed and managed according to which part imposes the power supply adjustment, the grid or the loads or a share of both. Especial considerations regarding this must be taken for those electric power systems with a large degree of HRES penetration [1–24] where maintaining voltage and frequency stability without some kind of power supply control mechanism based on intelligent load management strategies can be quite difficult. In addition to the flexible demand of energy users (loads), incentives are needed to make this feasible,

[4] *Note*: IEEE 519 "Standard Practices and Requirements for Harmonic Control in Electrical Power Systems," defined PCC as "the interface between sources and loads on an electrical system".

according to other authors [43,48,56–89], since there are goals sought by the energy consumers, especially residential, and the electricity suppliers such as user comfort, quality of power, and reduction of energy losses in the grid, or economic profit for both parties which are conflicting at times. When it comes to adjustment of consumption according to the user's needs, e.g. how to best manage the system response to a sudden drop or rise in load frequency triggered by an event, the consumer's power needs to be increased/decreased according to the portion of flexible demand. It is necessary to establish a criterion to modulate the consumption of several loads and to decide which and how much to increase/decrease in power [55]. In [54], it is mentioned that the increase in demand variability. In this regard several authors reviewed have done important research on grid-connected PV-wind systems as well as other RES and conventional sources mixed together in various configurations and sizes [1–84,86–88] proposing a variety of approaches regarding the intermittent nature of renewable generation and the compliance with grid standards. On another note, residential households everywhere use single-phase grid connection. Along this line, the paper *"Control strategies for single-phase grid integration of small-scale renewable energy sources: a review"* [92] provides a good review of the main characteristics of control strategies for single-phase grid integration of small-scale renewable energy sources of the kind needed to advance the penetration of DG in developing countries like Chile, particularly in so many rural areas of the country where electricity is quite costly. Likewise, Carrasco et al. [94] present a review on power-electronic systems used for single-phase grid integration [92,93] and synchronization control techniques with interesting findings and complementing views and arguments on the subject. Both papers discuss the single-phase grid synchronization issues pointing to the single-phase voltage source converter (VSC) as the best solution for interfacing with a single-phase grid, offering several advantages such as bidirectional power flow capability when there is excess capacity to inject back to the grid, as well as offering low distortions at the AC side current and the DC side voltage [88–118,120–130]. It can independently control the active and reactive power exchanged with the AC grid so as to improve the voltage profile, and it is able to operate in weak AC systems common in remote and rural locations where small communities live [88–118,120–130].

The paper *"Hybrid solar-wind system with battery storage operating in grid-connected and stand-alone mode: control and energy management—experimental investigation"* [95] presents experimental results from operation of a test bench for a grid-connected HRES. This device includes wind and photovoltaic (PV) physical emulators, battery energy storage, load and a controlled interconnection to the low voltage (LV) grid, most appropriate for residential electricity supply. Both Wind and PV generation units are connected to the weak AC grid via a single-phase inverter with a lead acid battery bank. Thus in the event of a power outage in the grid, the system automatically disconnects from it and switches the alternating current output over to a separate emergency output circuit with true sinusoidal output voltage [96]. Also interesting is the paper "A review on sustainable design of renewable energy systems" [96] presents the state-of-the-art in renewable energy systems design, specifically focusing on solar-based energy systems, ground source-based systems and day-lighting systems, to gain optimum performances in sustainable buildings, noting that there is good EE potential of such systems in reducing resource consumption. The premise here is that specific designs will influence the user's energy consumption behavior towards higher EE and energy sustainability. This view is particularly influenced by systems thinking and cybernetics [212–224] whereby organization, structure and technology choices are made in building sustainable systems architectures which are poised to condition users as complex adaptive systems (CAS) [226–230] to embrace and adapt to these new design trends (Fig. 3).

The paper *"Economic assessment of a distributed energy system in a new residential area with existing grid coverage in China"* [97] explains that when considering localized energy demand sources such as a number of homes divided in residential blocks, typical of rural locations in Chile, an appropriately designed DG system can have a number of advantages compared to the more conventional approaches of solely relying on connecting to the power grid to meet electricity demand [98]. For instance, the on-site production of electricity can minimize energy losses linked to transmission and distribution processes. DG systems may also reduce the need for grid expansion and added centralized generation capacity, thereby avoiding often difficult planning and construction processes associated with large plants and long distance transmission. When the distributed energy system is connected to the grid the system has higher efficiency and better economics than the more traditional approach of relying entirely on grid connection for electricity needs. This indicates that the complementary use of grid power is indispensable to distributed energy systems [97]. Another relevant paper is *"Distribution system operation supported by contextual energy resource management based on intelligent SCADA"* [32] explains that future distribution systems will have to deal with an intensive penetration of distributed energy resources (DER) ensuring reliable and secure operation according to the smart grid paradigm. SCADA (Supervisory Control and Data Acquisition) system [30,32,81,82] traditionally used in larger

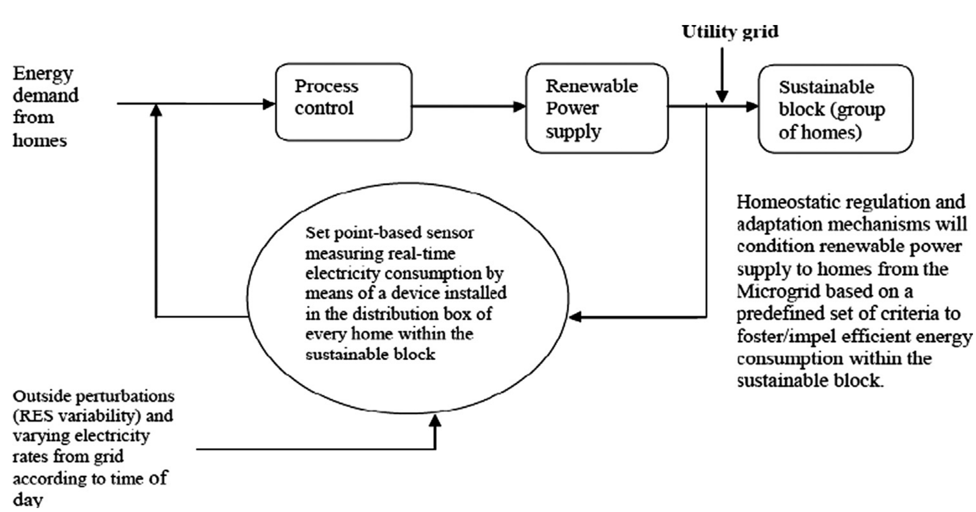

Fig. 3. Energy homeostasis regulation model through negative feedback for residential consumers without energy buffer.

and higher levels of power systems, to transmit measurements, status information, and control signals to and from Remote Terminal Units (RTUs) must be changed to play their expected functions at the core of the concept of smart grid and the grid of the future [5,8,22–33,36–90,93–167] and it is an essential piece of infrastructure for this evolution towards smart microgrids. Thus [32] proposes a new conceptual design of an intelligent SCADA with a decentralized, flexible, and intelligent approach, adaptive to what authors term *context awareness* [32]. The SCADA model presented supports the energy resource management undertaken by a distribution network operator (DNO). Resource management considers all the involved costs, power flows, and electricity prices, allowing the use of network reconfiguration and load curtailment. Authors point out also that the SCADA systems of the future ought to be designed to support multi-level decentralized decisions and actions of consumers (loads) and diverse micro-generation sources. The use of Internet and other wireless networks is envisaged for demand-side management, implementing residential load management in the context of smart homes. In this paper a conceptual design of an intelligent SCADA, with a more decentralized, flexible, and intelligent approach, adaptive to the context (context awareness) is used to support energy resource management in the context of future power distribution systems [27–35]. Likewise Refs. [55–89] focus on the energy management of small HEPS, where the adequate scheduling of the different energy sources is a crucial problem for which adequate methodologies can maximize the performance of the energy supply. Several innovative methodologies and techniques for DER management are proposed [55–89].

The paper *"Grid-connected versus stand-alone energy systems for decentralized power—a review of literatura"* [98] points out that the implementation of decentralized energy systems such as renewable microgrids depends on the extent of decentralization the country or region is seeking. At the rural and remote level, where thousands of small communities exist, decentralization of power systems is a good a viable option. In such locations the DG system can be managed by local players and energy is supplied to meet the local needs. The extent of decentralization also determines whether the system operates in either grid-connected or stand-alone mode [98]. Some important features of grid-connected systems are for example that grid-connected hybrid energy system is an independent decentralized power system that is connected to an electricity transmission and distribution system (utility grid). They are ideal for locations close to grid. In a grid-connected power system the grid acts like a battery with an unlimited storage capacity, and takes care of seasonal load variations. As a result of which the overall efficiency of a grid-connected system will be better than the efficiency of a stand-alone system, as there is virtually no limit to the storage capacity, the generated electricity can always be stored, and the additional generated electricity need not be wasted by means of a dump load. In addition to the initial cost of the system installation, there is also the cost of interfacing with grid which in developing countries like Chile, could very well be subsidized by the government as part of its energy decentralization policy. Upon reviewing the current status of GC and stand-alone HRES, the authors point out that, to the best of their knowledge, thus far there is perhaps no review presented on the studies focusing on assessing the feasibility of grid-connected and stand-alone energy systems. Other authors have also published reviews on decentralized energy planning models and energy models, respectively, but have not focused on grid-connected and on stand-alone systems without energy storage [98,99–161].

1.5. Microgrids

The paper *"General aspects, hierarchical controls and droop methods in microgrids: a review"* [99] defines microgrids as small, local distribution systems containing generation and load, the operation of which can be separated totally from the main distribution system (the utility grid) or connected to it [99] the paper reviews the main features of a microgrid and describes the characteristics of the control systems utilized, providing details of the control tasks involved along with the main types of controls proposed in the literature [11,33,39,41–67,79,83,92–95,99,101,108,113,133–136]. However, authors often warn that because of the intermittence, randomness and uncertainty of renewable energy sources (RES), it is difficult to integrate renewable energy sources directly into the utility grid. By integrating distributed and renewable sources, energy storage devices, a variety of loads, data acquisition and supervisory control devices, microgrids are the interface between the distributed renewable sources and the utility grid [1–13,54,92–130]. Hierarchical, centralized control of microgrids is the most utilized for load sharing between DGs, power quality, participation in the energy market, provision of ancillary services, etc. Such objectives can be achieved through a hierarchical control scheme of three levels. Among the experimental microgrids studied, it has been shown that most of the microgrids implemented use AC transmission systems with centralized controls. It has been also seen that islanded microgrids play an important role in rural electrification projects all over the world [1–128,147–172,176–208] where the power distribution network has not yet arrived. The paper *"A review on distributed energy resources and MicroGrid"* [41] ascertains that distributed energy resources (DER) comprise several technologies, such as diesel engines, micro turbines, fuel cells, photovoltaic, small wind turbines, etc. The coordinated operation and control of DER together with controllable and flexible loads and storage devices are central to the concept of microgrid, which can operate connected to the main distribution grid, or in an islanded mode such as grid-independent hybrid power generation systems [142]. This paper reviews the research and development work done on microgrid technology, where emphasis on the operation of the microgrid is given, warning that application of several individual distributed generators can cause several problems in frequency and voltage stability. Authors explain that the coordinated operation and control of such DER, together with controllable loads and storage devices are central to the concept of microgrid, which can operate connected to the main distribution grid, or in an islanded mode [41]. However, there are instances where energy storage devices are neither economically convenient nor desirable, and perhaps might not even be permitted in certain locations due to environmental restrictions, like in Easter Island. This paper also warns that application of several individual distributed generators can cause several problems. Therefore, in order to realize the emerging potential of distributed generation (DG) and associated loads, the microgrid may be better and more efficiently controlled by employing a distributed control architecture known as multi-agent system (MAS) [183,184]. Therefore, in order to realize the emerging potential of DG and associated loads the microgrid may be better and more efficiently controlled by employing distributed control architecture such as MAS. MAS technology can solve a number of specific operational problems. First of all, small DER units have different owners, and several decisions should be taken locally so centralized control is difficult. Furthermore microgrids operate in a liberalized market; therefore the decisions of the controller of each unit concerning the market should have a certain degree of "intelligence" [183,184]. In *"Multi-agent based techniques for coordinating the distribution of electricity in a Micro-Grid environment"* [184], the authors state that the rapid increase in demand for electricity – especially in developing countries like Chile – will need to be balanced with additional sources of power supply. However the current national grid in many countries is not capable of sustaining this rapid increase in projected demand, a challenge which is very much present in the Chilean national grid.

Therefore authors point out that a more dynamic and efficient two-way national grid will be required which incorporates intermittent renewable resources, micro-generators, micro-storage devices and agent managed microgrids. Fred C. Schweppe researched ways in which a dynamic national grid could be implemented. However at the time, the technologies available were quite limited [184]. This paper compares the current state-of-the-art techniques for solving some of the problems Schweppe identified, describes the agent coordination algorithms that are used, and suggests some future research opportunities on applying agent coordination algorithms, that have not previously been used, to microgrids [184] (Fig. 4).

The paper *"Microgrids: energy management by strategic deployment of DERs—a comprehensive survey"* [130] reports on existing research literatures in connection with various energy management issues and the benefits of a microgrid arising from strategic deployment of its DERs [130,131–141]. Survey on regulatory issues includes various barriers, incentives, standards (IEEE 1547, UL-1741, etc.), environmental issues, ancillary services and smart metering. Economic benefits, like improvement of bus voltages, frequency and line loss reduction, deferral of upgrade, waste heat utilization, reduction of customer interruption cost (CIC), emission reduction, and fuel cost minimization are all discussed here. Another paper, *"Technological innovation systems for microgeneration in the UK and Germany—a functional analysis"* [131] examines the deployment of micro-generation in Germany and in the UK from a technological innovation systems (TIS) perspective. Based on this, authors summarize supportive and obstructive factors and discuss the differences in the respective national setting for small-scale HRES and combined heat and power (CHP) technologies. The findings underline the importance of legitimating and institutionalizing the microgrid concept and the financial support needed for this. Micro-generation policy differences between Germany and the UK are also explained, comparing the former to the UK, where micro-generation enjoys little support [131]. The paper concludes that DG penetration will not be successful without a more focused and technology-oriented innovation policy [131], one that at least as far as the energy matrix decentralization policy of developing countries such as Chile are still lacking. On the other hand, the paper *"Microgrids research: a review of experimental microgrids and test systems"* [132] presents a review of existing microgrid test networks around the world (North America, Europe and Asia) and some significantly different microgrid simulation networks present in the literature, focusing on the test systems and available microgrid control options with emphasis on energy storage devices deemed critical for the reliable operation of a microgrid. The paper points out that communication and control strategies utilized in microgrids play a major role, allowing the advantage of treating the microgrid as a controlled aggregated load within the current power systems, especially with adaptive control approaches towards a smart grid system [132]. Interestingly, the paper by Outhred *"The smart grid: getting the incentives right"* [145] points out that the smart microgrid employs innovative products and services together with intelligent monitoring and control, communication and self-healing technologies where SCADA supervisory control can play a major role in the effort to

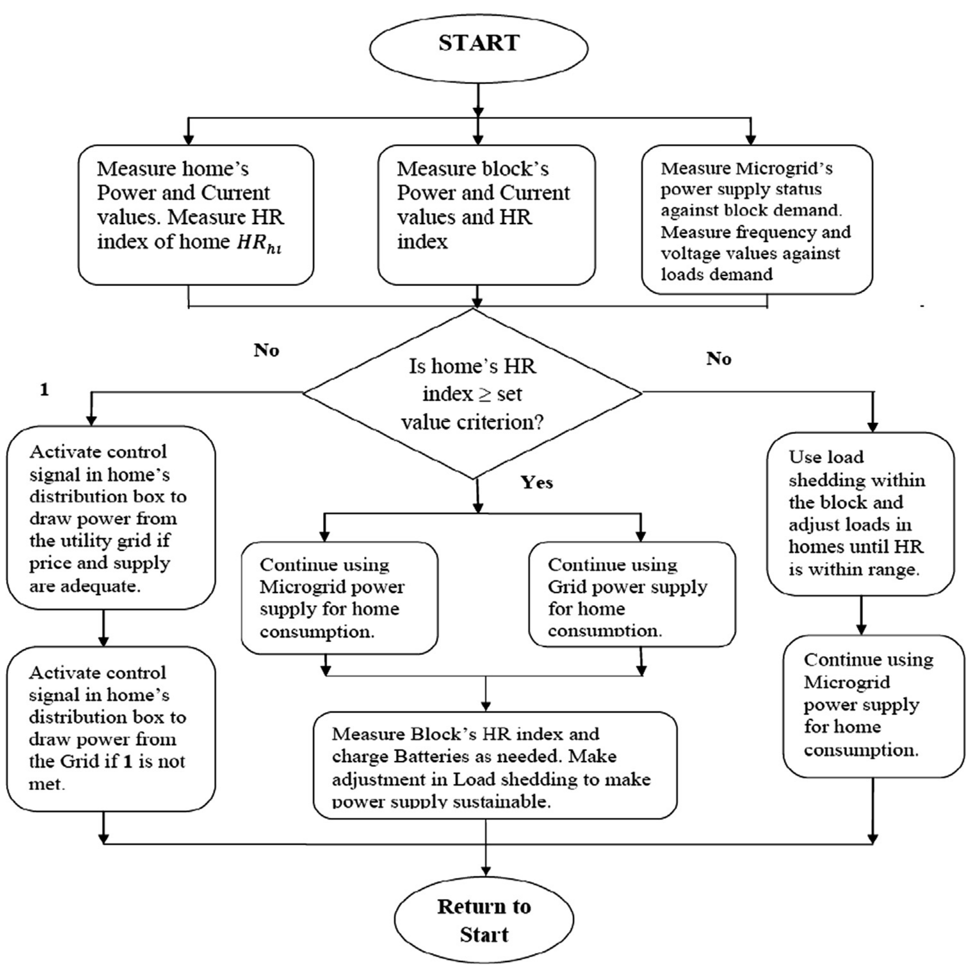

Fig. 4. Flow diagram of control logic with homeostatic regulation (HR) index as a key control feature for a grid-connected PV-wind hybrid micro-generation system with batteries, to supply electricity to a small group of homes termed a sustainable block in a rural or remote community.

find equilibrium between supply and demand of electricity in residential consumers. A smart microgrid should employ innovative approaches to achieve this. Caron et al. [146] also address the issue of incentive-based energy consumption management and focus on scheduling employing mathematical algorithms in the context of the smart grid. Indeed, looking at the near future on this subject, it is expected that such systems will use revolutionary new technologies, products and services such as smart metering to move towards a consumer-oriented approach especially for residential customers [43–89,92–118,140,141,143,161].

Another interesting paper reviewed is *"The research agenda on social acceptance of distributed generation in smart grids: renewable as common pool resources"* [110] explains that the rapid developing literature on smart grid technology suggests that these will facilitate DG preferably from RES [110]. However, authors warn that current development of smart microgrids with substantial number of DG sources suffers from too much focus on technology issues, lacking on other important considerations [110]. Institutional factors have proved to be the main determinants of acceptance in communities where smart microgrids and the use of RET in DG projects is increasingly associated with a more sustainable type of power supply. Ongoing problems with the deployment of renewable energy technologies (RET) have shown that implementation is largely determined by broad social acceptance issues and the review presented is a first attempt to address the social issues in building smart electricity grids [110]. According to major trends in DG literature, adoption of distributed multi-generation systems, DMGS may yield significant benefits in terms of energy efficiency [243] and reduced carbon emissions, due to the fact that DG combines geographically dispersed decentralized generation from preferably renewable sources [110], a scheme that would certainly prove highly beneficial for Chile. Along this path, Lund et al. in their paper *"From electricity smart grids to smart energy systems—a market operation based approach and understanding"* [5] warn us that the challenge of integrating fluctuating power from RES in the electricity grid using smart grids cannot be looked upon as an isolated issue but one that should be seen as requiring various means and presenting several challenges in approaching sustainable energy systems in general. Therefore, electricity smart grids must be coordinated with the utilization of renewable energy being converted into other forms of carriers than electricity including heat and bio-fuels as well as energy conservation and efficiency improvements, such as combined heat and power (CHP) and improved energy management efficiencies. Sustainability in DG systems is linked to strategies and measures which aim towards energy conservation and energy efficiency improvements. This article illustrates why smart electric grids should be seen as part of an overall, collective smart energy system and emphasizes the inclusion of flexible CHP production balancing and grid stabilization [5]. Basak et al. in *"A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid"* [42] predict that the concept of integration of distributed energy resources (DER) for implementation of microgrids will be most significant in the near future [42]. The latest research and development in the field of microgrid power systems is presented in this paper, showing a broad overview on the worldwide research trend on microgrid. The literature review reveals that integration of DER, operation, control, power quality issues and stability of microgrid system should be explored much further to implement microgrid successfully in real power scenario. Research teams of CERTS [169]. have greatly contributed to microgrid research focusing on the customer adoption of microgrid through a customer adoption modeling (DER-CAM) proposed. Energy management systems (EMS) are found to be an important feature of microgrid operation and control for maximum utilization and service to consumers [59,64,141].

In *"Recent developments in microgrids and example cases around the world—A review"* [147], the authors present a complete review of the microgrid background and concept, along with the current status of the literature, along with ongoing research projects, and the relevant standards in the subject. It also presents a review of the microgrid pilot projects around the world in further detail and discusses the potential avenues for further research. Depending on the type and depth of DER penetration, load characteristics and power quality constraints of a microgrid can be significantly and even conceptually different than those of the conventional power systems [147]. Likewise the required control and operation strategies can also change substantially. Hence, a microgrid is a dynamic entity – in essence a complex dynamic system capable of adaptation and self-organizing – and DG sources might connect or disconnect while the microgrid is in operation just as the microgrid may disconnect from the grid or control its energy supply according to certain power supply and energy demand criteria. When connected to the grid, the frequency and voltage values are dictated by the utility grid and DG units are operated to follow these set values, thus riding on the grid's frequency and phase angle values by means of the inverter. The paper advises that for microgrids to be more rapidly adopted, universally embraced and more easily implemented there is a need for systematic standardization in all aspects of the field [147]. It is important to make the whole process as visible and simple as possible [1–54] and to provide the incentives and the technology enablers necessary to make the system flexible and stable, very reliable in its energy supply function so consumers know exactly what to expect and when to expect it. Particularly in Chile, with its ambitious goals of integrating RES and technologies to the country's electric power distribution networks by 2020, microgeneration will need to become more widespread and with it, the need to make these energy systems more sustainable and reliable. For this it is important to device adequate and effective strategies to operate such systems integrated to the grid [54,92–110]. It is here that the concepts of energy efficiency (EE) and efficient equilibrium (homeostasis) come into play just as flexibility and stability must both co-exist in electric power systems (EPS) to make them more resilient and sustainable. They must be incorporated into the equation to make these systems more efficient and flexible both technically and operationally. If the characteristics of electrical power systems are built-in with the concepts of EE and equilibrium in mind, the chances of making more sustainable electric power systems (EPS) increases substantially.

But first let us discuss these ideas more in depth. Unlike other more conventional approaches [111,112], in this paper the focus is put on the structure, organization and operation of the HRES and its interaction and evolution as a coupled system with the grid and the sustainable block to which it supplies power in parallel with the grid, but offering a substantial economic and social benefit to rural energy consumers, who in the case of Chile, pay a high price for their electricity. In order for HRES to be sustainable, living systems – such as the microgrid supplying electricity to a group of homes – a socio-technical system in itself – the systems involved operating as a collective must be efficient in their energy intake and expenditure. The more thrifty and efficient they are, the more likely the collective system is to become more sustainable in the long run. However, for this to occur, the concept of *efficient equilibrium* (homeostatic regulation) in living systems based on homeostasis must be taken into consideration and thoroughly understood in the context of energy management of distributed electric power systems. A dynamic system may reach equilibrium yet not be efficient and sustainable, just like a fat person may reach an equilibrium condition in regards to his/her energy intake and expenditure, yet be far from healthy and efficient with respect to both. Likewise a complex dynamic system, such as a human organization for example, may also reach equilibrium in terms of

its resources supply and output of products and services yet it may be far from efficient and successful operationally and financially. However, an energy efficient living system such as the meta-system proposed in this paper, comprised of the grid-tie microgrid coupled to a sustainable block, must reach a sustainable, efficient equilibrium by means of homeostatic regulation and control. There is just no way around this, and it is here where the feedback loop, appropriate communication and control systems and devices and the important homeostatic control (HC) concept introduced by Schweppe [176,177] come into play in full force (Fig. 5).

Renewable energy technologies (RET) can be labeled as intermittent since they depend solely on RES and their inherent variability; therefore ideally they should be operated at maximum power output whenever possible. Upon reviewing several papers [1–161] where authors discuss the perspective of renewables in the making of strategies for a sustainable development, along with energy management in regards to energy supply and demand balancing, a variety of technical viewpoints are found. Such strategies typically involve three major technological challenges: energy savings on the demand side or demand response management, efficiency improvements in RET energy production, where much fruitful work has been done already and continues to be done; and replacement of fossil fuels by various sources of renewable energy. This last one in particular represents a long standing challenge that continues to be an uphill battle to this day, especially in developing countries like Chile. Consequently, large-scale renewable energy implementation plans must include strategies for integrating RES in a coherent manner designing appropriate energy systems that may be influenced by energy savings and energy efficiency [243] measures. Denmark is a good example of this, where renewable energy systems have made great strides thus far. Likewise when discussing flexible technologies to increase savings, EE measures and renewables, the problem of integration becomes important and must be taken into account in the design of the strategies to be implemented therein. Hence, the main problem which prevents a more widespread penetration of renewable energy technologies is the variability of the primary sources of renewable energy, mainly sun irradiance and wind, with never a steady output for long periods. Thus there is the need to complement each other and to add, whenever possible, a means of energy storage or a diesel engine to make the microgrid more dispatchable when it is possible and convenient to do so. Several strategies have been studied for minimizing the uncertainty effects, each one having different trade-offs between costs, environmental impact and easiness of implementation [97–161]. Likewise there are technical resources that can be built into the system as enablers such as smart/advanced metering systems [70,85,87, 146,147,148,195,196], which provide feedback to consumers in real time as a possible way to overcome intermittence of RES and achieving energy balance besides using diesel generators and grid support. For example, some solar water heating installations have associated display units showing water temperature and/or the

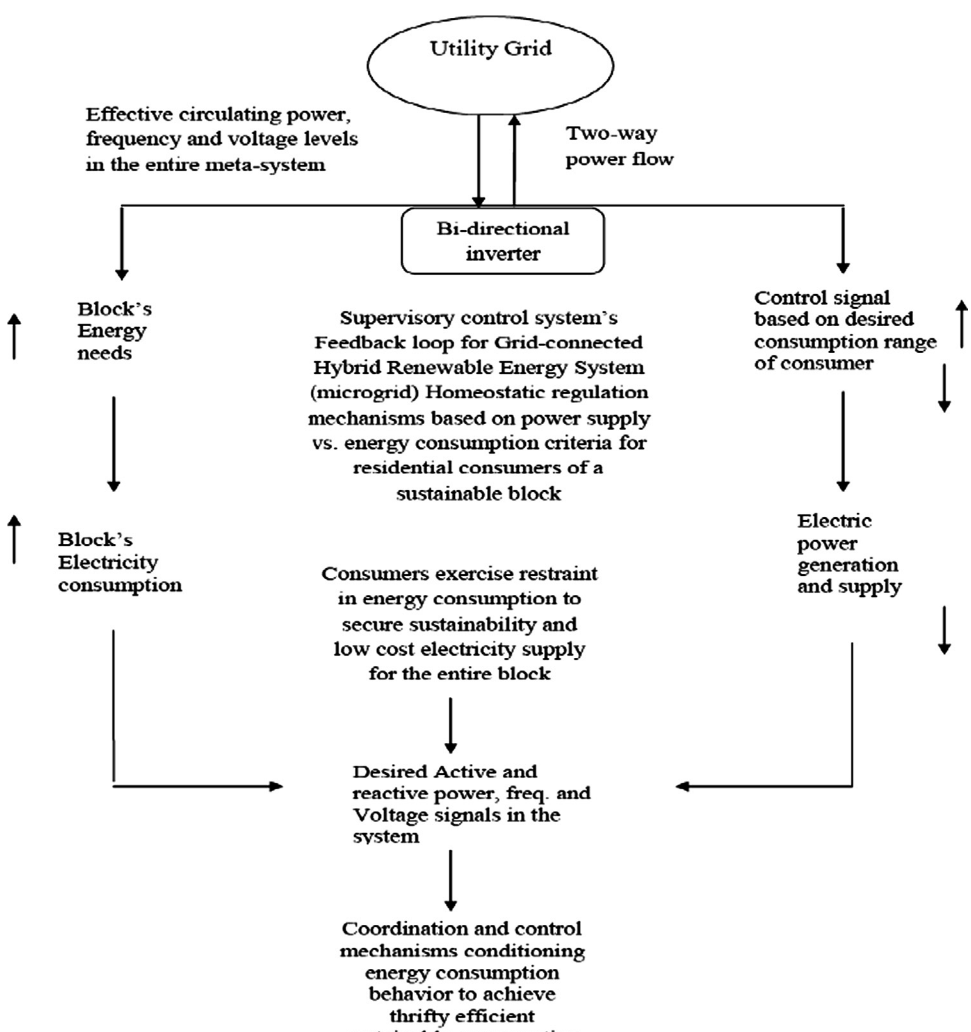

Fig. 5. Homeostatic regulation mechanisms in operation for a grid-connected hybrid renewable energy system (Microgrid) operating without energy storage.

amount of energy absorbed from the sun in a given period. Again, there are no norms as yet, but such displays do have a powerful effect in raising awareness on saving gas or electricity and keeping energy consumption low and thrifty.

1.6. Energy autonomy, sustainability and sustainable hybrid energy systems (SHES) in the current micro-generation context

Sustainability and sustainable energy systems are not the same, yet often times these two terms are intertwined and used almost indistinctively in the literature. Sustainability may not necessarily be understood as the same thing when dealing with sustainable hybrid energy systems (SHES). For SHES to exist, particularly in the case of those connected to grid, the concept of *built-in sustainability in energy systems* is of paramount importance and must be thoroughly understood, along with the effective management of energy flow and EE towards *equilibrium* in energy supply and consumption (energy intake and expenditure). We look at SHES (a grid-tied microgrid for example) connected to a group of consumers in a rural community somewhere, not as a sustainable socio-economic system but rather as a dynamically complex socio-technical system, a dynamical system capable of self-organizing, adapting and evolving towards a more flexible, resilient and motive-driven system [108–130,225–230]. This is in line with the whole concept and views on DER and NCRE explored in the literature review. Indeed a system that is comprised of people (loads), power infrastructure and technology, all integrated into one single entity – *a smart meta-system* – where consumers in the sustainable block, the renewable microgrid and the grid are mutually dependent systems, closely intertwined and constantly interacting and evolving as complex adaptive systems (CAS) [225–230] in a transition towards energy sustainability. Such interaction of consumers in a rural community – whether these may be small industrial or residential or a mixture of both – with the microgrid aims to achieve an efficient equilibrium between power supply and demand – brought about by the supervisory control strategy being proposed based on homeostatic control – something which is vital for making this whole socio-technical system more efficient and sustainable over time (Fig. 6).

Another important paper reviewed is *"Energy autonomy in sustainable communities—a review of key issues"* [152] presents a state-of-the-art review of the current research relating to energy autonomy in sustainable communities and identifies a number of central issues which are regarded as being of critical importance. Demand-side management (DSM) is identified as one particular area in need of further research and development, along with the need for receptive social, political and regulatory environments [152]. Likewise their study appears to suggest that from both financial and technical points of view, grid connection is highly beneficial [32] as opposed to stand-alone HEPS. In this regard, Kaundinya et al. [98] identify a number of disadvantages to stand-alone systems, such as the need to be able to run at low capacity

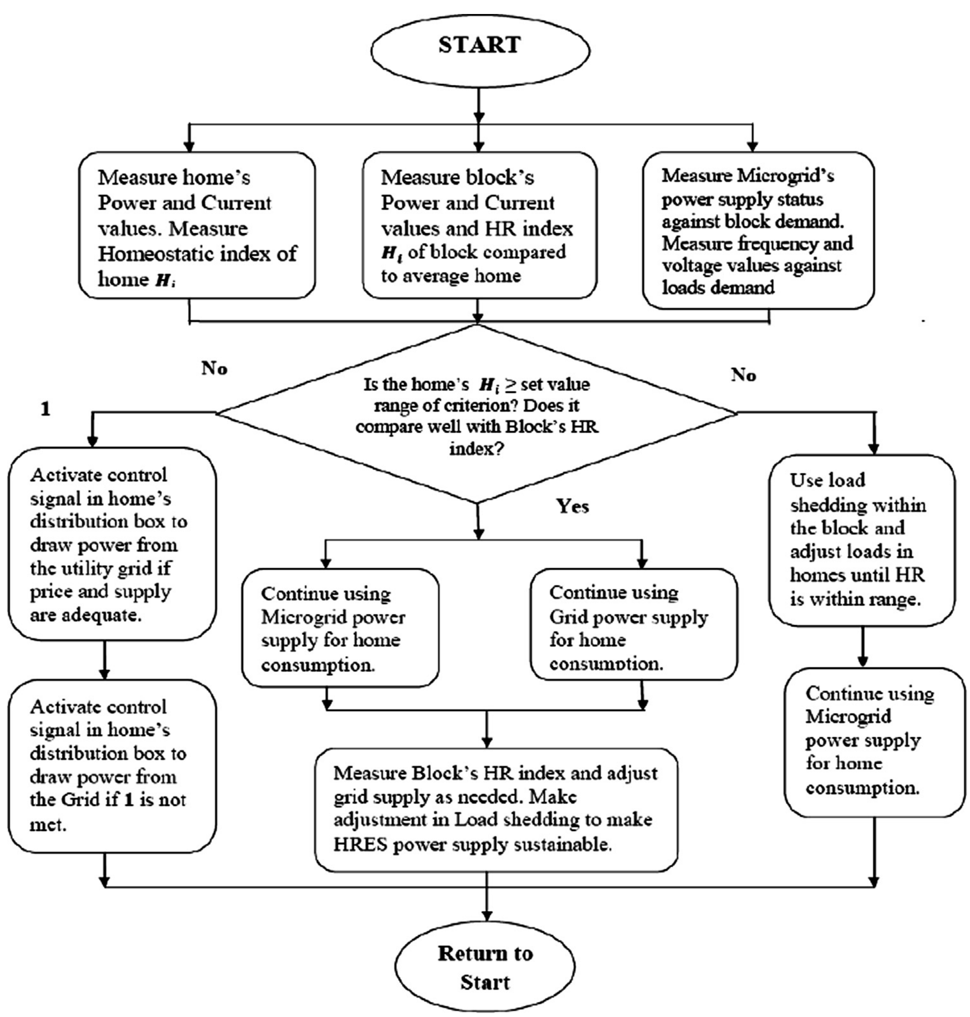

Fig. 6. Flow diagram of control logic with homeostatic regulation (HR) as a key control feature for a grid-connected PV-wind hybrid micro-generation system without energy storage, to supply electricity to a small group of homes termed a sustainable block in a rural or remote community.

factors, the high cost and technical uncertainty associated with energy storage and the possibility of having to "dump" excess energy that cannot be stored [98]. Clearly in a small rural community which depends on a HEPS connected to the mains it would be a waste and highly inefficient to dump excess electricity on a dump load. There are several other alternatives in which such excess power can be used like heating water, heating or cooling, manufacturing processes, water pump operation, water purification and desalination plant, among others. Authors also acknowledge the long-term economic feasibility of the DG project. In this regard it is much more cost-effective and technically/operationally convenient to have the local grid as back-up instead of having just an energy storage system like a battery bank. Furthermore, there are many locations – and Chile has several of these – where the contamination factor is an issue upon which the community has all their eyes fixed. There are various pollutants that can emanate from a battery bank or other similar chemical storage devices that employ various metals and chemical compounds which may degrade, leak and pollute the environment. The island of Chiloe and Easter Island are but two examples of this concern. Other means of energy storage are much too expensive and lack sufficient capacity thus obliging to purchase a number of these with the added financial burden for the project. To this one can add the technical drawbacks of some energy storage devices with respect to dispatchability. The batteries are readily dispatchable yet several other devices are not. They are slow to respond to sudden load increases or to act upon low capacity of the HEPS power supply at certain times of day when RES may vary considerably. All these issues present inconveniences and drawbacks which further complicate the benefit-per-cost analysis of such projects which ultimately play a decisive role in the decision to utilize grid-connected or "stand-alone" energy systems. When it comes to micro-generation systems for supplying power to small communities anywhere, energy demand and consumption behavior is particularly important when considering how to attain sustainable energy systems. In energy sustainability lies implicitly somehow the concept of energy autonomy and self-sufficiency. The authors in [152] also explain that non-autonomous systems can rely on external energy generation or storage; autonomous ones must be capable of meeting energy demands without the need for external support. The inherent intermittency of most forms of renewable energy adds another layer of complexity to this challenge by creating often frequent and potentially highly disruptive temporal mismatches between supply and demand. By taking greater control over energy demand, it is possible to improve the match between energy demand and supply profiles, and gain more control over the system in general [152]. It is important to add that the approach to energy autonomy and energy sustainability followed in the current work in regards to HEPS for small rural and remote communities power supply – in the context and vision explored herein – does not oppose grid-connection nor does it see a hindrance in energy autonomy in its use. Much to the contrary, it endorses it as not only a perfectly valid option and a much more economically sound and technically convenient one in many respects than the stand-alone alternative. This is especially true in developing countries like Chile, with a long and rugged territory, the country nevertheless has a good power distribution infrastructure in place. Therefore in light of what has been discussed so far, and considering the view presented here in this paper, the energy autonomy and sustainability issues embraced by the theoretical model and vision of the current work rest upon the consumers and their energy consumption habits, not just on the HEPS itself or on a magic device that can make all decisions for them. It is way they use energy from the system that matters most. Thus there will be consumers who will demand more and perhaps better quality of electrical energy and heat than others and who are willing to pay for this and there will be others that, given the cost of consuming more electricity from the grid (and/or more heat from the CHP unit), especially at certain times of day when the electricity rate is higher due to the peak demand hourly block and will prefer to exercise thriftiness and be more energy efficient, consuming not more than enough to maintain their energy bill low, drawing much of the energy they need from the HEPS and only using the grid in limited fashion at times of greater need. There is always a trade-off in everything in life as there is never a free lunch. Therefore it appears that while highly autonomous, stand- alone type HEPS are a theoretically desirable goal, in practice and when considering all restrictions and costs involved, they can be an often expensive [98,152] but technically feasible solution. Thus grid-connected HEPS with some degree of autonomy can bring a host of socio-economic benefits to the community but ultimately, the highly context-specific nature of such projects means that the degree of autonomy targeted is likely to be dictated by local factors [152] rather than by purely technical ones. One area of society where the benefits can be seen as being both highly applicable and highly relevant is at the community level and at this scale in particular, increased levels of energy autonomy can deliver a host of social, financial and environmental benefits. Therefore, the concept of energy autonomy is widely regarded as an effective tool towards sustainable development, with sustainable communities often highlighted as particularly relevant for applying its principles [152]. Along a similar line, the paper *"On the planning and analysis of integrated community energy systems: a review and survey of available tools"* [91] discusses the "Integrated Community Energy Systems (ICES)" concept, ICES are the means by which rural and remote communities – like those so common in Chile, upon which this paper is focused – can procure affordable hybrid micro-generation systems with CHP and other features which are capable of delivering sustainable electricity, heating and cooling to small rural and remote communities. Such systems can work as stand-alone systems or work parallel with and connected to the electricity distribution network as already discussed, and constitute a viable and desirable alternative towards achieving sustainable energy systems for such communities. An overview on tools for the optimization planning and analysis of Integrated Community Energy Systems (ICES), addressing special concerns to the incorporation of the environmental, economical and social aspects of Sustainability are presented in Refs. [90,91]. Likewise Afgan and Carvalho in [156] *"Sustainability assessment of a hybrid energy system"* discuss sustainability assessment presenting a method to evaluate the quality of the selected hybrid renewable energy systems (HRES), explaining that in such evaluation only a limited number of options are selected to demonstrate the sustainability assessment method application in the promotion of the specific quality of the hybrid energy system. The indicators used are: economic, environment, and social yet no mention is made of assessing more technical and operational aspects such as efficient equilibrium between power supply and demand response management neither are strategies presented to advance towards more sustainable energy systems in regards to reconciling electricity supply and consumption in the use of HRES. The authors in [156] argue that the sustainability issue ranges from the policy making in the top to the engineering practices in the bottom, with a top-down approach to the subject. However, their approach is intended for contributing to the development of a bottom-up approach to energy sustainability of HRES in the European context in particular.

Das and Balakrishnan (2012) in their paper *"Sustainable energy future via grid interactive operation of spv system at isolated Remote Island"* [29] favor feeding renewable electricity to the utility grid through grid-connected HRES, during time of peak power demand,

arguing that sufficient electrical loads can be shed to prevent turning on a coal or natural gas-fired plant [29]. This paper analyzes the case of a region of West Bengal, India where a proposition is made to find out the possibility of grid-connectivity in a remote island which is under the rural electrification scheme by means of HRES under Jawaharlal Nehru National Solar Mission of India. In these rural electrification program, grid extension can be the best option if the grid is reliable, the rural community rather big and in proximity to the grid. In many circumstances, a strong case for mini-grids based on hybrid systems can be made. In Chile in particular this has become a concern due to the high price of electricity – the highest in all Latin America – and the effects on quality of air in urban and rural regions of the country with a sharp increase in the number of automobiles on the streets in addition to the rise in public transport vehicles. Thus the threat of disrupting and endangering living standards and environmental conditions which may adversely affect the large agricultural sector present in the central and south of Chile, and where the wine industry is a major player along with eco tourism. In light of this there is a need that is being addressed by the government and supported by the community at large to advance in the integration of DG and NCRE. Therefore small-scale decentralized DG systems [1–130] are being envisaged as a viable alternative to conventional, grid-only power supply all over the world. In this regard HRES are becoming an alternative to the centralized electricity distribution networks scheme, adding more flexibility and aiding the advancement of sustainable energy systems in the current electric power infrastructure and contributing to fight pollution and (green house gases) GHG from fossil fuels. In this context, the engineering of sustainable energy systems provides a methodological scientific framework to arrive at realistic integrated solutions to complex and diverse energy problems, by adopting a holistic, systems-based approach, especially at the decision making and planning stages regarding design, analysis, configuration, and modes of operation [89–93].

An interesting concept, similar to the model being introduced by the present paper, is presented and discussed at length in the paper *"The Energy Box: Locally Automated Optimal Control of Residential Electricity Usage"* [160] The "energy box" is a supervisory control device incorporated in the HEPS and proposed as a 24/7 background processor, operating on a local computer, much in the same way as the Homeostatic Regulator being proposed in the current work for rural and remote communities, silently managing one's home or small business electrical energy usage hour-by-hour and even minute-by-minute. It operates best in an environment of demand-sensitive real-time pricing, now made feasible via "smart grid" technology [160]. The *energy box* [160] is an interesting concept and offers a solution which is based on a "smart" device like other approaches. However in this case it is more interesting since it allows consumers intervention in terms of making energy demand more flexible. Thus the system supports graceful reductions in power consumption by allowing voluntary partial load shedding as requested by the electric utility during times of extreme high demand; favoring the implementation of demand-sensitive pricing strategy that allows for a more personalized supply of electricity, providing more and better service alternatives within the capacity constraints of the current system infrastructure [160–171] (Fig. 7).

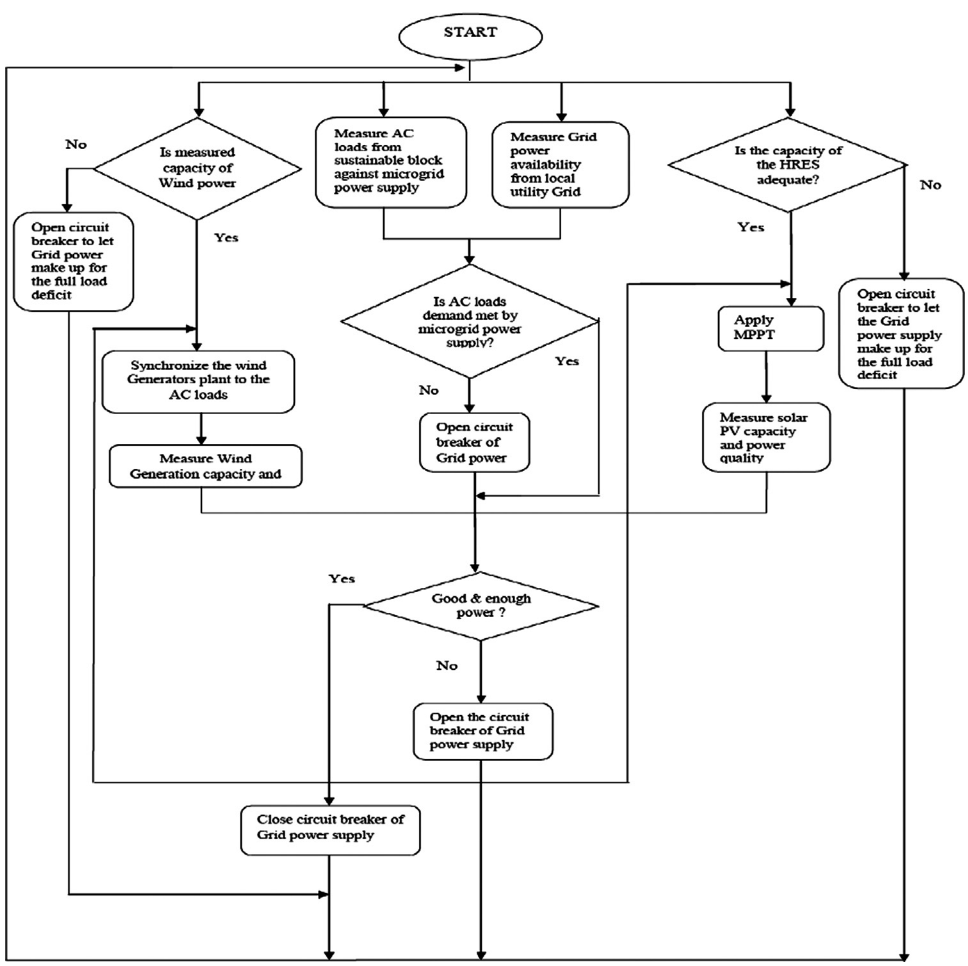

Fig. 7. Flow diagram of supervisory control logic for a grid-connected solar PV-Wind HRES without energy storage.

1.7. A view towards sustainable micro-generation systems

Often the problem with HRES is that traditional approaches to integration of NCRE necessarily involve breaking into the local environment of the place in one way or another, usually attempting large-size interventions, most of the times power utility oriented, which may cause much environmental and social upheaval in the local community's way of life. Such interventions may threat the ecosystems and produce undesirable consequences such as acoustic and visual contamination – highly feared in various locations of the north and south of Chile for example – brought about by big wind turbines (with the noise of the turbine blades as they spin, especially when they are large) and large PV panel arrays occupying huge extensions of land. Such are some of the projects being proposed today for the Atacama Desert in Chile for example and there are other proposals for the far south as well. In such cases the site is drastically intervened with massive DG installations literally invading the landscape. An example of this almost took place in the island of Chiloe, located on the far south of Chile, where an entrepreneur was legally stopped by the loud clamor of the local community and forbidden from carrying out such an intervention. To this must be added the fact that Chile in particular has several unique ecosystems like Easter Island and the Chiloe Island, among several others which are both beautiful and fragile, thus protected by existing Chilean law and local regulations.

In reviewing several papers on HRES, particularly small PV-wind energy systems, as well as microgrids design and management of a variety of hybrid micro-generation systems (HMS) and distributed resources towards sustainable energy systems [1–171] authors present different approaches within the current state-of-the-art in microgrids design and configuration as well as the barriers that are being encountered for their integration to the grid in certain cases. They assert that expectations of the microgrid performance are high, thus, issues related to the microgrid standards, autonomous operation, control strategies, regulatory barriers as well as its protection and islanding operation are all discussed, along with other relevant aspects. However nothing is said in regards to possible means and ways of turning microgrids into sustainable energy systems. They point out that one of the technical challenges that microgrids face lie in the availability of low-cost technologies for a safe and reliable operation, again emphasizing the economic aspect as so many others have done. Likewise, the microgrid ownership issue is also discussed and regulatory policies are mentioned as important hindering factors in the proliferation of these micro-generation systems. Another important issue discussed in the review on microgrids is the design considerations needed to produce a sustainable energy system, where authors often emphasize the need for using a combination of different RES which has the advantage of greater balance and stability, where the wind is usually stronger in winter and during nighttime, whereas solar irradiation is much higher in the spring and summer seasons and during daylight. A balanced system provides stable outputs from sources such as these and minimizes the dependence of the output upon seasonal changes. Therefore it is clear that the use of different RES may bring a more economically feasible, stable and efficient HMS given that renewable energy on a small scale is still a relatively expensive option compared to conventional, fossil fuel-based energy systems. However, no precise or in-depth analysis is offered on how technical and operational aspects of such systems can contribute to making them more sustainable with the active participation of consumers as central players. It is also pointed out that due to the present costs of implementing RET solutions to gradually replace traditional energy sources to meet the increasing energy demand – large wind farms being the exception yet a very costly one – it is still not cost effective compared to the use of conventional fossil fuel-based energy sources or where electric power is supplied by the electricity distribution network. However, they fail to notice one important fact that needs to be fully accounted for. Aside from the fact that non-conventional renewable energies (NCRE) have a strong environmental appeal all over the world, especially in countries like Chile where they are abundant and where environmental concerns are a main issue of discussion, there is also the fact of dispersed population settlements everywhere. In Latin America in general and Chile in particular, there are large numbers of rural settlements, mainly small-size communities scattered everywhere, that must pay a high price for electricity supplied by the utility grid or by other fossil-fuel based energy sources. The reason for this, aside from an electricity market with a very small number of players offering service, is the transport of electricity and fuel over very large distances, which contributes significantly to the problem of high cost of electricity. Therefore, on top of what we have discussed so far regarding energy and systems sustainability, this fact brings an additional argument in favor of building more sustainable energy systems [89–171] such as HMS employing innovative strategies that are technically and operationally sound and also feasible. Finally a very interesting and enlightening paper reviewed is the one by Ding and Buckeridge titled *"Design considerations for a sustainable hybrid energy system"* [128] where emphasis is put on cost–benefit analysis as a factor that has to be incorporated into the design process of HRES. Authors add that "If an exchange of material, energy or information occurs between a system and its surrounding environment, the system is termed open. By its very nature, a hybrid energy system is open, too, because the inputs include the effects of the environment" [128]. "Without these inputs from the environment, the system will not function properly" [128]. "The inputs of an open-loop system are independent of its outputs, which are not linked to its performance. As such the system cannot regulate itself. On the other hand, in a feedback system (or closed-loop system) the outputs have influence on the inputs, and feedback is generally used for control. As a result the system can control itself and is sustainable." [128]. This becomes especially meaningful and true when it comes to enticing and influencing energy users to change their consumption habits towards greater EE and energy sustainability.

Therefore, in light of the literature reviewed thus far, devising strategies aimed at facilitating greater energy autonomy and sustainability does not appear to have been fully explored at present, as opposed to energy generating technologies and to a lesser extent, energy storage technologies which have both received much more attention in terms of research focus within recent years. Thus the potential associated with demand response management and control via supervisory control systems, employing an array of economic incentives based on merit strategies for fostering and impelling greater EE and thriftiness in energy consumption is a virgin field where there is still much to be done. There is therefore a need to investigate the ability of demand side or response management to facilitate and improve energy autonomy in sustainable communities in greater detail and to examine its social, economic and environmental impact as well.

2. Sustainable micro-generation systems (MGS) by means of cybernetics and homeostatic control

Cybernetics as a concept was first introduced by Wiener [223], and later in 1959, Beer [224] made important contributions to the field of management cybernetics, thus adding much perspective and further insight onto the subject and its possibilities therein. Both have greatly influenced the current paper right along with Schweppe [57,67,176,178,180] along with his collaborators

[177,179,181] working on homeostatic control (HC). HC is a term introduced by Schweppe and his group of collaborators at MIT back in 1979 [176–181] and further developed by them in the early 1980s. It stems from the highly visionary work done by them at a time when technology was quite limited. In fact they were ahead of their time, having a true insight for what was to come in the years ahead. HC is based on the idea that homeostasis regulation and control mechanisms apply in electric power systems when viewed as dynamically complex adaptive system. Indeed a grid-connected hybrid micro-generation system (HMS) supplying electricity and heat to a group of residential consumers in a rural location somewhere may be looked upon as a dynamically complex socio-technical system – a meta-system if you will – when the three interconnected systems are taken together and analyzed as a systems coupling scheme, comprising one adaptive meta-system – a system of systems. This becomes particularly true and complex in cases where micro-generation power systems operate without energy storage, connected to the mains and supplying power to a set of residential customers as an integrated system with the current electric power infrastructure, operating as a complex socio-technical system—a meta-system if analyzed from a systemic and cybernetics viewpoint. Such systems, as already pointed out, may be treated as complex dynamic living systems which continuously interact with their environment as open systems, seeking to regulate and adapt their energy production and expenditure as needed, just like living organisms do when influenced by homeostasis regulation (HR).

2.1. Self-regulating, self-organizing complex adaptive systems (CAS)

The Complex Adaptive Systems (CAS) model was born of the scientific study of complexity. According to Gleick [225], the inspiration for complexity science can be traced to John von Neumann's dynamic weather system models of the 1950s at the Institute for Advanced Study in Princeton, New Jersey. Complex adaptive systems are a special case of complex system. Complex because they involve a high degree of diversity and abundance of information, where systems are made up of multiple interconnected and interrelated components or parts, sometimes involving well defined hierarchical relations amongst these parts that are usually not evident to the observer, and that as a whole, exhibit one or more properties which may conform some type of behavior not obvious from the properties of the individual parts. Complex adaptive systems (CAS) are fluidly changing collections of distributed interacting components that react to both their environments and to one another. Examples of complex adaptive systems include the electric power grid, telecommunications networks, the Internet, biological systems, ecological systems, social groups, and even human society itself. Many of the multidisciplinary and interdisciplinary problems found within these systems are of such great complexity that traditional modeling methodologies are often considered inadequate. Complex systems are based on relationships, and their properties of self-organization, interconnectedness and evolution. Every energy consumption system within a higher-order system is unique and must be understood as an individual whose adaptive capacities to become more efficient and effective are dependent upon its structure and its interaction with the environment in which there are other systems some of which contain this individual one. Complex adaptive systems and open systems exchange energy with their environment, and can change and adapt based on responses to the exchange with the environment in ways that go beyond cybernetic systems. Although in the field of cybernetics complex adaptive systems are not equivalent to living systems, they can be thought as such and can certainly emulate them and operate under similar principles [225,226].

2.2. The concept of homeostatic control of electric power systems

The concept of Homeostatic Utility Control utilizes the economic response to price on the part of suppliers and consumers combined with today's technology in the fields of communication, computation and supervisory control to develop an efficient, internally-correcting control scheme based on homeostasis regulation. Homeostatic utility control, as described by Schweppe et al. [178] and emphasized by Sterling et al. [179] and Tabors et al. [181] is "an overall concept which tries to maintain an internal equilibrium between supply and demand." and it seeks to do so by informing the customer of the time-varying prices of electricity, whereby the customer can make his/her own decisions independently as to when, how and how much to consume, as opposed to having conditions being imposed to him/her as it normally happens even to this day with small residential customers as well as with small and medium-size commercial customers especially in Chile, a country where electric power generation and distribution is in the hands of a few. According to Schweppe and his group "It is to the advantage of both the customer and the utility that the electric power system be planned and operated as economically and physically efficiently as possible subject to constraints on environmental quality and on system integrity" [176,177]. They basically argued that it was to the advantage of both the customers and the utilities that more cooperation and assistance between the two were allowed to exist [176–181], and that somehow, a co-evolution of interests and perspectives of both parties should emerge, seeking to conciliate both sides posture in benefit of the industry and the community as a whole. This revolutionary change for the time meant that an adequate regulatory and technological scenario had to be in place to support such change, indeed the kind one hopes to see in Chile some day. In such scenario customers could communicate with and be informed by the power supplier, whether this may be the local utility grid or a renewable microgrid operating in parallel and connected to the grid through a bi-directional inverter. Such scenario envisaged by Schweppe et al. [178] would allow customers to have more freedom on their decision making as energy users instead of having "big brother" as they put it, decide for them [176,178]. We know now of course that this was all to change, although at a slower pace than expected—energy efficiency(EE) [243] being a telling example of this much slower-than-expected change. Today's technology no doubt allows this to happen and should be complemented with an adequate regulatory framework behind it, like the type of legislation being analyzed and proposed today in Chile for NCRE integration into the country's energy matrix. However, back in those days this approach was quite novel, remarkable and truly visionary and quite ahead of its time (Fig. 8).

Here it is important as explained earlier, to provide real-time information to the user and to the control operator, making the whole process as visible as possible and allowing choices to consumers according to the HRES capacity at any point in time, along with the price of electricity supplied by the local grid.

Along this very same line of thought, recently there came a paper by Ramchurn et al. titled "Agent-based homeostatic control for green energy in the smart grid", [182] and another titled by the same authors "Agent-based control for decentralised demand side management in the smart grid" [68] both which are based much on the same principles and ideas initially put forward by Schweppe and his group, but this time focusing rather on the smart microgrid which is injecting power to the utility grid, and analyzing the issue of HC from a customer demand response management. In Ramchurn et al. [182,68], the authors present a new control mechanism to model and control a HRES in a microgrid configuration injecting power to the grid and also supplying power to a number of individual homes each having a battery bank or similar energy storage device. According to the

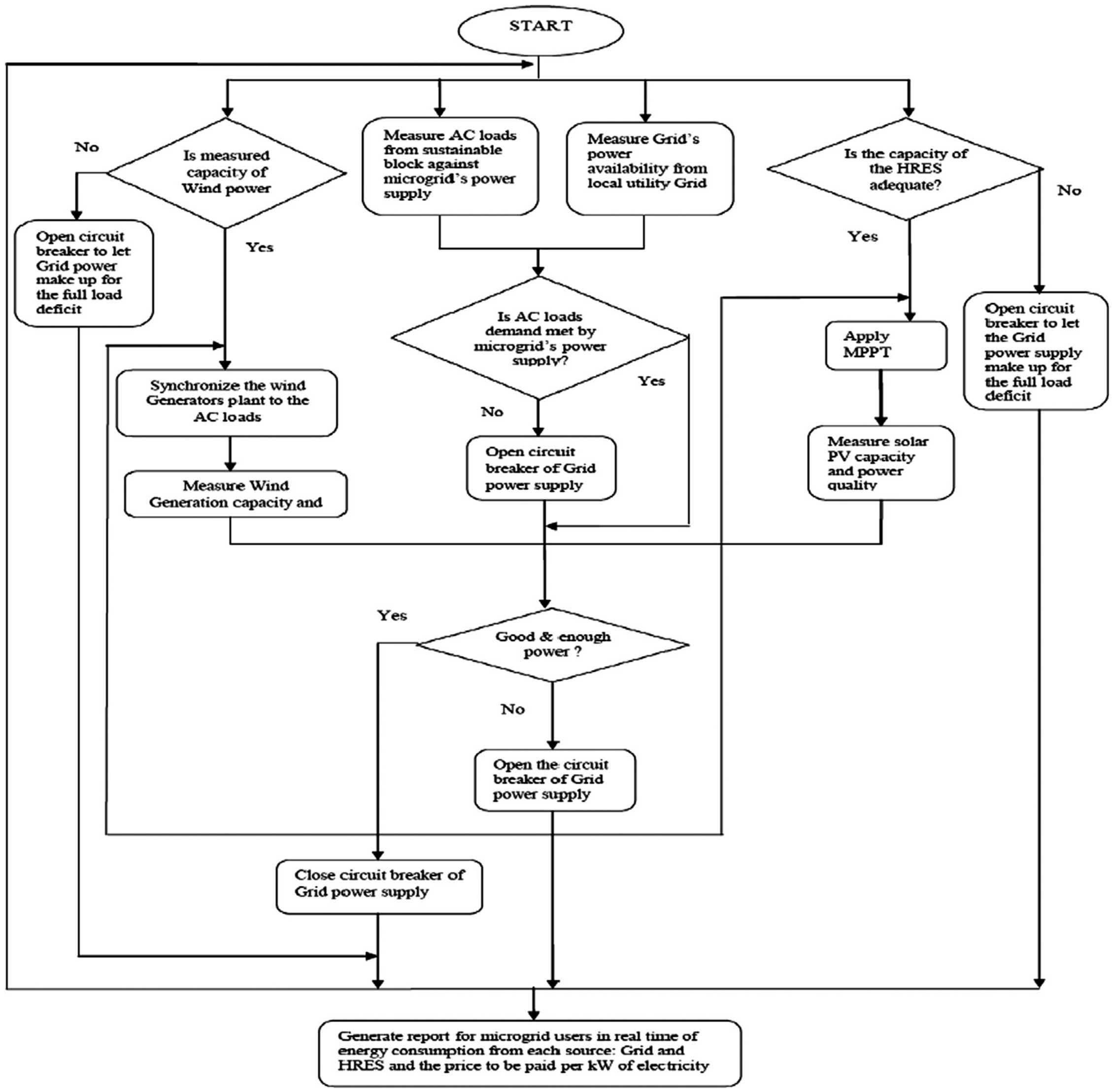

Fig. 8. Another view of supervisory control logic for a grid-connected solar PV-Wind HRES without energy storage.

authors "this control mechanism is based on the concept of homeostasis whereby control signals are sent to individual components of a system, based on their continuous feedback, in order to change their state so that the system may reach a stable equilibrium" [182]. Their approach aimed to define a new carbon-based pricing mechanism for this renewable electric power supplier which takes advantage of readily available information on the internet that can be accessed by consumers [182]. This information, in the form of carbon-intensity signals, is made available to consumers in order to provide real-time pricing to them, thus allowing them to make decisions on whether to use stored power instead of the grid supply or to switch to grid at a time when rates are cheaper and power is being injected to the grid or is less available in the energy storage units [182]. This is supposed to incentivize agents to shift demand (load shedding on the customer side) using the extra capacity built in their storage devices to times when renewable energy is more available and stable in its supply. This is interesting as an experiment and may provide some insight into a hypothetical future for residential settings, when residential energy storage devices could become affordable, and someday perhaps be just like any other home appliance, making their way into the homes and small businesses and be a practical means of power supply at times of need (e.g. a power outage due to system fault or a natural event) or a better option to resort to when prices of the utility grid power supply are high. However it is also true that with the price of energy storage systems today of the size and characteristics necessary for every home to have such energy storage capacity built into their electricity management system, as it is proposed by these authors, along with the use of smart-metering, it seems unviable, unpractical and rather far-fetched. Likewise, a carbon-based pricing mechanism as the one being proposed is also less feasible and certainly not a priority in developing and underdeveloped countries, as well as in most developed nations as of today; and it is likely to never find its way into electric power distribution strategies and policies for low-density population areas, of the type so abundant and widespread in Latin America, especially in small rural communities upon which this work is particularly focused. This will also require that renewables be well integrated in the current electric power generation infrastructure and massively used as a second source of power supply for grid-connected energy systems such as microgrids, which operate in tandem with the main grid and also inject power to it in times of surplus.

A complex adaptive systems (CAS) approach to grid-connected microgrids aims to manage these as a living organism where coordination and control mechanisms act as key enablers of homeostatic regulation to achieve the type of efficient equilibrium (homeostasis) between electric power supply and energy demand

and consumption, just like Schweppe and his group proposed back in 1979. When it comes to grid-connected HRES operating at the micro-generation level, one can expect diverse power consumption scenarios where environmental and systems operation change continuously and randomly for the most part. Because of this constant and continuous change, it is necessary for the system to have adaptive capabilities built into it so that it may no longer be just another complex system but a smart complex adaptive system. A system that is both active and responsive to the individual needs of the different residential consumers and also to the local grid with which it is coupled. Such HRES should possess an intelligent coordination and control strategy that is incorporated in its supervisory control system which would allow the microgrid to sustain itself while supplying power and prevail against such common variations as those characteristic of changing weather conditions and energy supply and demand. These random and continuous changes, both in the microgrid itself and in environmental conditions – most notably sudden climatic changes more common now than before – which may affect the capacity of the microgrid to generate and supply good, stable quality electric power steadily to the homes and eventually to the main grid if capacity should allow it.

2.3. The homeostatic index concept in sustainable hybrid renewable energy system

With respect to homeostatic regulation (HR) in grid-tie HRES operating without energy storage, given the nature of the system configuration where only the grid operates as back-up and no means of energy storage are present, it is important to pay particular attention to the concept of energy autonomy already discussed, which in this case bears special significance. Given the latter, it is both pertinent and necessary at this point to introduce a new concept with regard to SHES and energy sustainability. The concept introduced here in this paper is termed homeostatic index (H_i). H_i is a measure of how much electricity is being drawn by each home in the sustainable block from the utility grid. This is measured as a percentage of the total electricity (renewable plus non-renewable) being consumed by the home with respect to the average block's electricity consumption. It is basically a parameter measuring both energy efficiency (EE) and *thriftiness* as a measure of *energy sustainability* in residential consumers. Therefore it is also a good measure of how effective (homeostatic regulation) HR is operating in the whole meta-system (the homes connected both to the mains and to the microgrid) at any point in time. It is important to discriminate between energy drawn from the grid and energy drawn from the HRES for the residential consumer, since the concepts of energy sustainability and energy autonomy are both imbedded therein, along with the economic implications that such choices have for consumers. Homeostatic index shows how thrifty and efficient each home is and therefore it also measures if the supervisory control strategy based on power supply and energy consumption equilibrium criteria being employed is working or not and how effective it is. This can be examined at any point in time with respect to the renewable power supplied by the microgrid with respect to the amount of electricity being drawn from the grid. A value below 1 and closer to 0.80 is considered acceptable yet ideally one seeks values closer to 0.60 or 0.50 and below as a true indicator of a high degree of thriftiness and EE for the home.

The paper "*A possible Engineering and economic framework for implementing demand side participation in frequency regulation at value*" [64] proposes an extension of today's Automatic Generation Control (AGC) to enable the participation of consumers in the demand response management context towards frequency stabilization and regulation, much like the FAPER [176–181] invented by Schweppe and his group at MIT. Schweppe et al. [178] introduced a device termed the Frequency Adaptive Power Energy Rescheduler (FAPER) conceived to assist and perhaps even replace conventional turbine-governed power systems and spinning reserve for electric utilities. Their paper, "Homeostatic utility control", was indeed revolutionary for the time and their approach sought to achieve faster, more flexible and efficient electricity supply–demand balancing by employing this "governor-type" mechanism provided by the FAPER on certain types of loads that, at the time, used conventional metering. These could be replaced according to Schweppe et al. [178] by a "Marketing interface to customer (MIC)" model which, in addition to measuring power consumption, multiplies that consumption by posted price and records total cost informing the customer in real time how much the electric bill will be for that particular power consumption. Thus, the customers retain the freedom to select their consumption patterns according to their needs and subject to different rates per time-of-day pricing [57,67,68,139,176–182]. Especially in such cases as having many RET and energy sources operating in tandem, the authors in [55–66] suggest that frequency and voltage stabilization can be achieved by beginning to rely on various means of automated frequency regulation employing what is termed "demand responsive loads". These are essentially flexible, smart loads that employ a feedback (cybernetics) loop continuously feeding information back to the parties which comprise the meta-system. Thus they are willing and able to adapt their necessities in terms of electricity and space heating and cooling in the community, changing their energy expenditure habits to make the meta-system more sustainable, basically turning it into a SHES when combing the conventional power supply of the grid (or a diesel generation plant as it is commonly seen in remote places) with the HRES. They stress the fact that as more and more intermittent energy resources get deployed, particularly those integrated to the grid, it becomes necessary to account for their fluctuations, in much the same way as the AGC accounts for load fluctuations at present [63,55–66]. They also address the concept of smart loads, and their unexplored potential so as to harness frequency-response capabilities of these smart loads in the power systems infrastructure [55–66]. This is necessary to balance supply and demand as well as to follow the fluctuations of diverse renewable energy resources. Information technology and advanced sensing/metering infrastructure makes realization of demand response feasible. While the concept of homeostatic control introduced many years ago is hard to apply to hybrid energy systems, according to the authors, because they have a mix of many diverse technologies, particularly if their sizes vary significantly [55–80] it is interesting that authors ascertain, looking ahead, that with an increase in DG and smart load components plus the need to deliver renewable generation across large electrical and geographical distances, new models will be needed to better understand and monitor power imbalances both for their location and temporal variations [55–80].

Renewable/alternative energy sources have very different operating characteristics; it is, therefore, essential to have a well-defined and standardized procedure for connecting them together to form a HRES, or more widely, a renewable microgrid, tied to the grid where a local cluster of DG sources, and perhaps energy storage devices if there are no site restrictions in place like in Easter Island. Under such scheme loads may be integrated together like a cluster, such as a residential block, and be capable of operating semi-autonomously. As part of this scheme, a robust microgrid should have a so called "plug-and-play" operation capability (be easy to install and connect to the existing system and ready-to-run in little time), and also be modular, flexible and portable, should it be needed elsewhere. Adapted from the concept widely used in computer science and technology,

"plug-and-play" operation here means a device (a DG, an energy storage system, or a controllable load) capable of being added into an existing system (microgrid connected to the main utility grid) without requiring system reconfiguration to perform its designed function, namely, generating electricity and heat as needed, providing energy storage capacity when appropriate and feasible in terms of environmental and site regulations, or carrying out load control. There are many ways to integrate different NCRE power generation sources to configure and install a HRES. The methods can be generally classified into three categories: DC-coupled, AC-coupled, and Hybrid-coupled [130,131]. The AC-coupled scheme can further be classified into power frequency AC (PFAC)-coupled and high-frequency (HFAC) AC-coupled systems only used for high frequency applications (≥400 HZ) [130,131]. Thus, what is used in modular small HRES for household's applications is power frequency AC (Figs. 9 and 10).

Each rural community has its own characteristics motivations, and incentives. Therefore the particular criterion designed to be implemented in the supervisory control system of the grid-tie micro-generation system operating without energy storage has to be tailored to the community's needs and aspirations. This specificity and individuality considerations must not be ignored as they are at the heart of the new approach to sustainable hybrid energy systems (SHES). The approach is linked to energy efficiency (EE) and thriftiness as drivers and enablers of such a strategy to be introduced in the community, but much more complex and difficult than managing the energy generation and supply from the microgrid and its complementary and alternative role with the grid power supply is the management of peoples energy needs and the management and control of adjustment/adaptation of energy consumption patterns in rural communities to use these SHES more effectively and efficiently, especially due to their variability. It is also worth mentioning that the analysis done here, in terms of HC strategy to manage renewable power supply from the SHES operating in tandem with the grid, totally ignores transmission constraints and emissions implications, which may be an important assumption made, as shown in several articles [235–242].

2.4. Microgrids as sustainable hybrid energy systems (SHES)

Various aspects and technologies for microgrid control strategies were reviewed [1–89,90–118,120–171]. A very detailed and thorough analysis is done in *"A review of hybrid renewable/alternative energy systems for electric power generation: configurations, control, and applications"* [108], where the authors present a review of hybrid renewable/alternative energy systems focusing on energy sustainability. It highlights some important issues and challenges in the design and energy management of such systems, emphasizing that outputs from various generation sources of a hybrid energy system need to be coordinated and controlled to realize their full benefits. Different coupling schemes find their own appropriate applications as well, depending on the mix of sources and loads being present. If major generation sources of a hybrid system generate DC power like photovoltaic (PV) panels, and there are also substantial amounts of DC loads, then a DC-coupled system may be a more convenient choice. On the other hand, if the main power sources generate AC (with reasonable power quality for the utility grid and the connected loads), then an AC-coupled system is the way to go. If the major power sources of a hybrid system generate a mixture of AC and DC power, then a

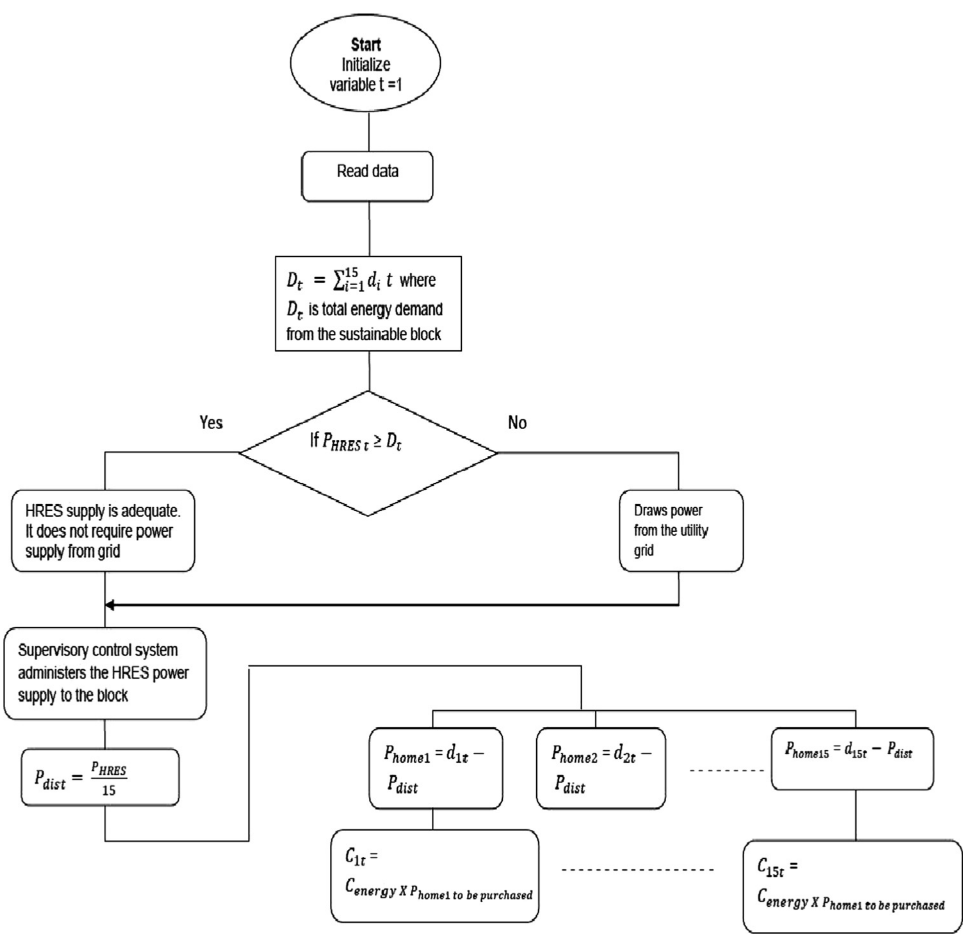

Fig. 9. A portion of a generic algorithm devised to efficiently control the renewable electricity to be supplied to residential consumers in a rural or remote community.

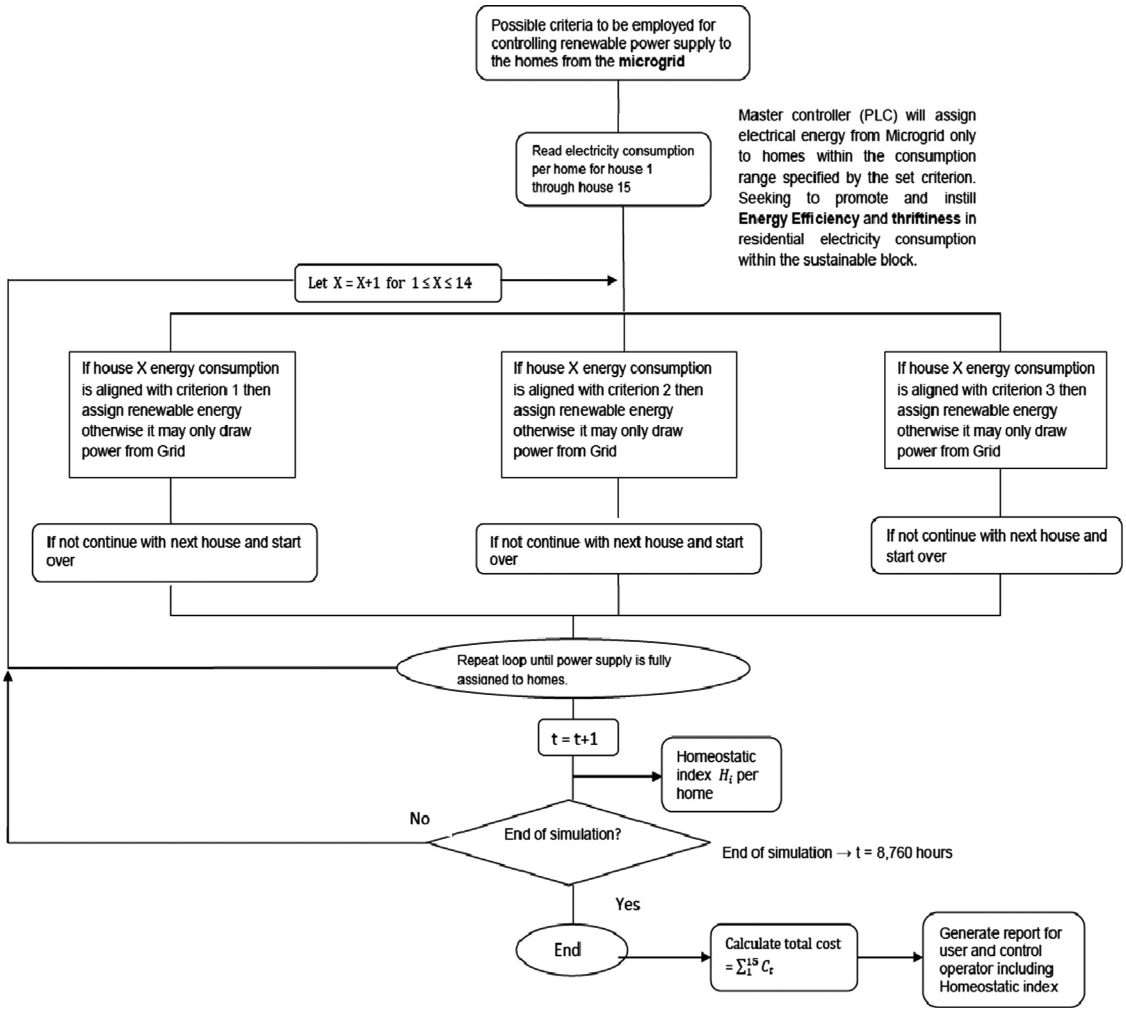

Fig. 10. A Homeostatic control approach can employ a number of criteria devised specifically for different communities in very different locations.

hybrid-coupled integration scheme may be considered. Both DC-coupled and AC-coupled systems' configuration are explained thoroughly, along with advantages and disadvantages or each. The system can supply power to the ac loads (50 or 60 Hz), or be interfaced to a utility grid through an inverter, which can be designed and controlled to allow bidirectional power flow in cases where there is surplus capacity on the HRES to inject power to the mains. The DC-coupling scheme is simple and no synchronization is needed to integrate the different energy sources, but it also has its own drawbacks. For instance, if the system inverter is out-of-service, then the whole system will not be able to supply AC power. To avoid this situation a solution is proposed, connecting several inverters with lower power rating in parallel, in which case synchronization of the output voltage of the different inverters, or synchronization with the utility grid if the system is grid-connected, is needed. A proper power sharing control scheme is also required to achieve a desired load distribution among the different inverters [108]. AC-coupled systems can be divided into two subcategories: Power Frequency AC-coupled and High Frequency AC-coupled systems, used mainly in telecommunication systems. Thus the different energy sources are integrated through their own power electronic interfacing circuits to a power frequency AC bus. Coupling inductors may also be necessary between the power electronic circuits and the AC bus to achieve desired power flow management. Another choice is to use Hybrid-Coupled Systems (HCS) configuration in which instead of connecting all the DG sources to just a single DC or AC bus, the different DG sources can be connected to the DC or AC bus of the HRES. In this configuration, some RES can be integrated directly without extra interfacing circuits, such as wind energy while others need double interface like PV. As a result, the system can have higher energy efficiency and reduced cost. Nonetheless the authors warn that on the other hand, control and energy management in such coupling might be more complicated than for the DC- and AC-coupled-only configuration [108,130]. A key component to grid-connected HRES is the inverter which operates in phase with the grid (unity power factor), and is generally delivering as much power as it can to the loads – whether these are residential consumers or the grid or both – given the available RES and system capacity. Again it is clear that current research is quite focused on making mini and microgrids smarter, more resilient, self-healing, more flexible and resourceful when viewed as a collection of interacting systems that are coupled at critical nods [108,130]. Interestingly, the paper *"Autonomous control of microgrids"* [165] embraces a systems thinking approach to microgrids, stating that a better way to realize the emerging potential of DG is to take a systems approach which views generation and associated loads as a subsystem or a "microgrid" [165] and where the microgrid which is coupled with a group of rural consumers and is working in tandem with and parallel to the grid, constitutes a higher-order system, interacting with yet another higher-other system: the grid. Thus the energy sources comprising the microgrid can operate in parallel to the grid or can operate in island mode, providing additional services such as uninterrupted power supply. The Consortium for Electric

Reliability Technology Solutions (CERTS) microgrid control concept is included in this paper. Such concept is driven by two fundamental principles (1) A *systems* perspective is necessary for customers, utilities, and society to capture the full benefits of integrating distributed energy resources into an energy system; and (2) The *business case* for accelerating adoption of these advanced concepts will be driven, primarily, by lowering the first cost and enhancing the value of microgrids [165]. The paper argues that the microgrid concept enables high penetration of DG with the current conventional power distribution systems allowing flexibility and compatibility between both. When the microgrid is connected to the grid, loads receive power both from the grid and from local micro-sources, depending on the customer's situation [165].

3. On the implementation of sustainable hybrid energy systems (SHES)

On [103] *"Grid-connected hybrid PV/wind power generation system with improved DC bus voltage regulation strategy"*, it is stated that among various types of RES, the solar and wind energies are the most promising ones for human beings. Due to the rapid growth of the power electronics techniques, the photovoltaic (PV) and wind power generations systems have increased rapidly. Because of the inherent nature of the solar energy and the wind energy, the electric power generations of the PV array and the wind turbine are complementary. Therefore, the hybrid PV/wind power system has higher reliability for delivering continuous power than either individual source [103]. In many configurations of HRES, a battery bank is used to draw maximum power output; however, the use of batteries is not an environmentally and aesthetically friendly solution, as most people know, because of their heavy weight, bulky size, high costs, limited life cycles, and chemical pollution. Therefore, the best way to utilize the electric energy produced by the PV array and the wind turbines is to connect them to the AC main grid directly [103]. Different circuit topologies for the grid-connected hybrid PV/Wind power system are shown in the paper. Since the output voltage of the PV array is different from the one of the wind turbine and the maximum power point tracking (MPPT) feature is demanded, a DC/DC converter and a DC/AC inverter are both needed for the PV/Wind power system. The paper shows an AC-shunted grid-connected hybrid PV/Wind power system using two individual DC/DC/AC converters. Each one is capable of delivering maximum power produced by the PV array and/or the wind turbine. However, no communication strategy among systems working as a collective is discussed whereby the systems involved can play a role regulating, adapting and assisting each other to achieve a common goal as a smart collective system of systems – a smart meta-system – that transcends the purely technical-components sphere. Much to the contrary, almost exclusively like in vast majority of papers, HRES components and their role in the operation and control dominate the discussion. In order to operate effectively, HRES in the form of a grid-connected microgrid supplying power to a group of homes in a sustainable block must be able to coordinate and utilize their limited resources to deal with uncertainty and complexity effectively, following certain strategic guidelines. These socio-technical systems must be able to acknowledge the tensions between flexibility and stability forces operating within them, and then manage them in a way that best reflects the strategy sought to make the system as sustainable as possible, from an operational standpoint. As pointed out earlier, the meta-system is comprised of the grid-tie microgrid, the sustainable block and the mains. Both flexibility and stability, depend on the meta-controllability of the socio-technical system, and it is the role of the supervisory control to be implemented for the HRES, and whose control actions are triggered by set-points upon being reached, to determine when and how much renewable power is supplied to a particular load based on the consumption range exhibited by consumers. This particularly efficient, thrifty energy consumption behavior on the part of consumers is elicited by means of a well defined energy generation and supply strategy which in part has to be implemented through certain predefined criteria, employing the concept of HC linking these criteria to specific strategic needs and objectives of the meta-system. It is the system's designers and engineers who are called upon to establish the right balance between stability and flexibility in the HRES, understanding that both are desired properties or qualities of the socio-technical system. Such properties must be engineered in the system itself – built into it – instead of adding them onto the system by incorporating more components. Such properties do not oppose one another – contrary to what some might think – but complement each other well if utilized in the right balance. Perturbations and uncertainty from within or outside of the HRES may come at any time since RES-based hybrid energy systems by nature are intermittent in their generation unless provided with readily dispatchable fossil–fuel energy sources and/or rapidly dispatchable energy storage devices like a large battery bank. Thus the need to be connected to the mains and/or or be provided with adequate energy storage or with readily dispatchable, fast conventional power generation sources such as diesel engines. Such perturbations and uncertainty may come at any time from within or from outside of the system or both, affecting the system's stability and flexibility, and possibly compromising its objectives therein, thus testing its resilience. In light of this, the approach chosen to build such properties seeks to control the renewable power supply to the homes by means of particular merit criteria which can be engineered in the system through reward incentives whereby consumers get inexpensive power supply form the renewable microgrid if they are able to keep their energy consumption within a certain range. Such strategy can be designed as a control algorithm for the supervisory control of the microgrid and programmed in the PLC for its implementation. The idea behind this approach is to reward thrifty, efficient energy consumption of electricity supply, tying it with EE and greater autonomy, in order to avoid having to purchase too much expensive electricity from the mains. Here one can see behavioral adaptation at play as a means to exert control over certain parameters in hybrid micro-generation systems (HMS).

Below is one of several criteria experimented with by means of computer simulation on Matlab 2010. In the example shown next, to illustrate the model for the purpose of simulating the system sustainability strategy being proposed, there is a grid-tie microgrid which is connected through a parallel network to a group of homes termed *a sustainable block* in a rural location of Chile. From this renewable microgrid consumers may satisfy if not all at least a good part of their electricity consumption needs (close to 80% in average for this particular hybrid system's configuration and sizing). First it is argued that in order to build a more flexible, diversified and sustainable and decentralized electric power infrastructure, DG systems in the form of grid-tie microgrids must be implemented with a supervisory control strategy capable of conditioning consumers energy use efficiently, allowing them the choice of consuming inexpensive yet limited power supply from the HRES, by keeping their consumption low or else consuming more power from the mains but at a high price compared to the microgrid supply. Such a strategy also seeks to reconcile power supply and energy demand in a way that preserves the sustainability of the system as a whole allowing consumers to make their own decision as to when and which electricity source to consume from yet preventing them from over consuming, especially from the grid supply. The strategy proposed is intended to foster EE and elicit a particular behavior on the part of energy consumers which calls for thriftiness and energy sustainability consciousness, looking to make the whole socio-technical system – a complex dynamic system in itself – more adaptive, flexible and sustainable over time. For this it is essential to

understand that new design, planning and control strategies ought to emerge [11–118,120–200] which may allow innovative technical and operational visions to exist, leaving behind from the traditional main stream road. This is not only necessary but crucial if we are to truly reach for the development of sustainable RES-based microgrids in rural and remote communities, using a sound energy sustainability philosophy as guiding framework. Below is the nomenclature for the simulation of the criterion shown below as an example of several such criteria. The criterion is explained following the diagram (Fig. 11).

3.1. Nomenclature

i	Home
t	Time (h)
m	Month (m)
P_{HESt}	Power generated by HES at time t (kW)
d_{it}	Power consumption of the home i at time t (kW)
D_t	The block's power consumption at time t (kW h)
$\bar{x}_{lower}$	Lower rank of eligibility range based on average value ($\bar{x}$)
$\bar{x}_{upper}$	Upper rank of eligibility range based on average value ($\bar{x}$)
N	N denotes the set of homes which comply with the set criterion
SUM	Sum of the power demand of the 15 homes comprising the sustainable block
P_{homeit}	Power bought by home i at time t (kW)
$\bar{t}_m$	Average time for house i having to purchase power (how much time in average was power purchased from the mains).
$\bar{t}_{m-1}$	To start for m, −1
$\overline{P}_{im}$	Average power purchased for house i in the month
C_{iSB}	Cost for the whole sustainable block

The system reads the power supplied by the hybrid energy system and the energy demand of each home in the sustainable block (15 homes). Then it calculates the total energy demand of the block, as time t moves on, towards a complete cycle of 8760 h in a whole year's worth of simulation. Then the system computes the average energy demand for the entire block and then makes a decision based on a rule that considers the energy demand of each home and compares it with the average demand, taking for this example 100 W as the average daily consumption of the block against which each home's demand is compared. This is directly targeted as a measure of EE and thriftiness of consumers in regards to the power supply capacity of the HRES and with respect to reaching for the alternative yet expensive energy source, drawing more or less power from the grid. Here is where the Homeostatic index comes in as a relevant measure explained earlier (Fig. 12).

As already stated, in this particular criterion used here only as an example of several such criteria, a condition is set up which states that if the demand of a house 0.*X* kW≤d_{it} is greater than or equal to a certain value to be predefined for the control system monitoring (consumption is kept within a specified range), then the house is or is not eligible to receive renewable power supply from the microgrid. However a further condition is introduced here that enhances the regulation mechanism by the systems involved and this is done by the cost calculation but this time in regards to the average time of power being purchased by the house from the main grid, as it is shown in the flow diagram's right below Here the amount of electric power purchased during a whole month from the mains by house i is computed by the summation $\overline{P}_{im} = \sum_{\bar{t}_{m-1}}^{\bar{t}_m} P_{\text{homeit}}$. Then there is a condition being set by the supervisory control system strategy for assigning supply of renewable electric power to the homes within the sustainable block. This condition states that if electricity consumption by home i is less than or equal to a certain threshold or boundary limit (e. g. 75 kW h for a tiny community in this particular case), that is $\overline{P}_{im} < 75$ kW h then if Yes, condition is met and the cost function will determine that the house pays nothing as it is being subsidized by those homes which consume over that limit. Thus there is a merit mechanism based on consumption range that fosters and incentivizes thrifty, efficient electricity consumption in the community, and

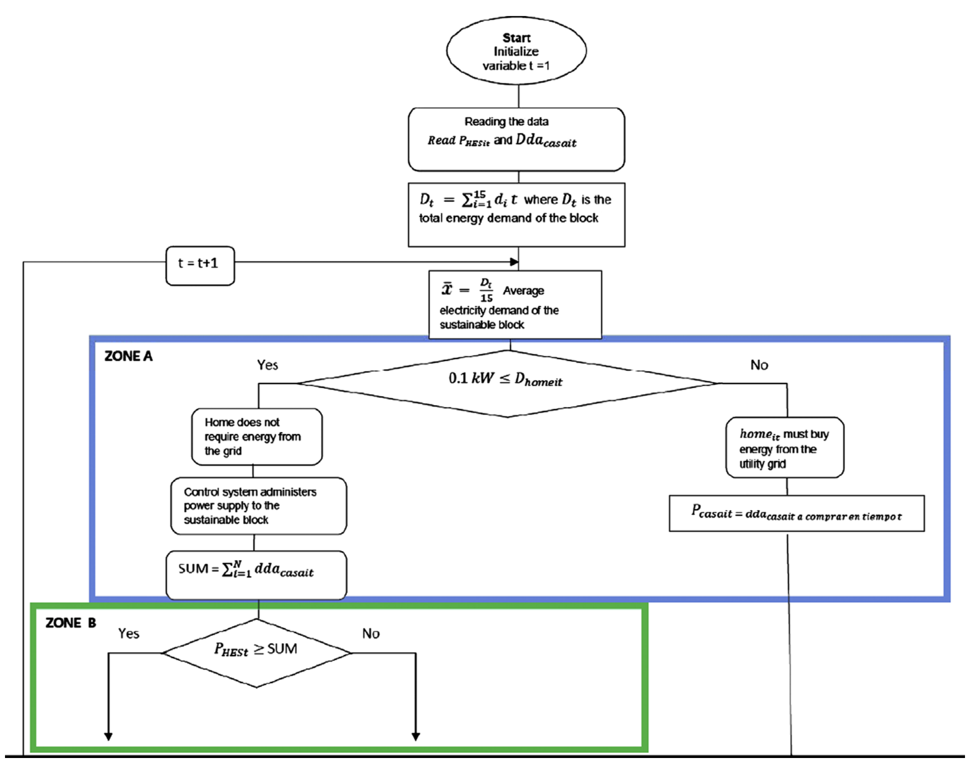

Fig. 11. An example of an algorithm employing a defined criterion to efficiently control power supply to homes. Flow diagram for Criterion 4 to illustrate the Matlab programming code for the simulation.
Note: 1 year simulation cycle δt=1 hour, where t=8760 hr in 1 year.

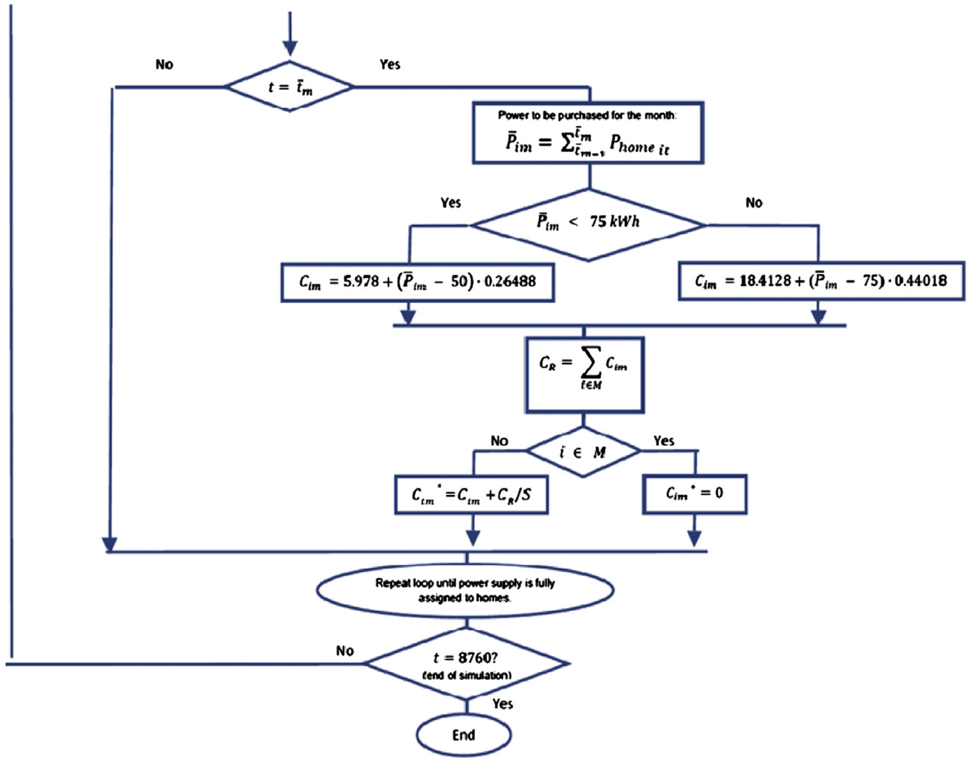

Fig. 12. Above is the second portion of the criterion shown above. It is but one of several criteria that can be employed to manage renewable power from the microgrid to a group of homes comprising a sustainable block. The algorithm can be implemented in Matlab programming code and simulated accordingly.

rewards the homes which consume less than a certain borderline amount. This way the strategy seeks to keep cost reasonably low and the overall meta-system sustainable from the power generation and supply standpoint. Likewise, the cost functions and values used here are just an example which illustrates the case for a particular location scenario. These cost functions can be designed in a wide variety of ways using different cost-benefit schemes and pricing strategies, all of which may vary significantly from one place to the next, as there are various rates and pricing schemes being used by utilities everywhere. This is true also for smaller suppliers using hybrid DG systems for electricity production, depending on the location, time of year, size of population, cost and means of electric power production, transport and transmission costs, etc. Yet the basic idea that the supervisory control strategy applied here is seeking to convey to consumers is that restraining consumption (being energy efficient and thrifty) is worth merit and must be rewarded. This particular criterion says that the microgrid will supply and charge for renewable electric power to the homes based on a certain threshold or boundary limit of electric power consumption, which is considered thrifty and very efficient in terms of electricity consumption for this particular community based on its monthly average energy consumption. In this portion of the criterion shown below, used as an example, we have yet another condition for costing which says that the cost of renewable electric power $C_R = \sum_{i\in+} C_{im}$ for the month is summed up for house i and then asks if house i is within M, where M denotes the set of homes with a monthly energy consumption less than 75 kW h. This is illustrated in the diagram portion below. In one case the total cost of electricity for house i is zero where in the other case the cost for the house is based on how much renewable power consumption it had for the given month).

3.2. Smart micro-generation systems (SMGS)

Smart micro-generation systems belong to the type of applications called smart grids. Smart grids are understood as the key technology that can enable the development of renewable energy sources and improvements on energy efficiency (EE) [109–119,121–130,193,197,227,233,234,243]. It can be called a transformed electricity grid (transmission and distribution levels) that uses *bidirectional communication systems*. The concept of smart grid can be utilized to define a diverse group of applications, which fosters the ability to monitor and control an electricity network (US Department of Energy, 2010) [231]. There is no unique definition of smart grid, even though it is easily distinguished from a conventional power grid [161–206,231]. However one can easily recognize that just about any definition on the subject points to an entirely different system from the conventional, archaic electric power systems we grew up with. Yet, when examining the literature on the subject, particularly on microgrids, one realizes that there is much emphasis on technological means to make the smart grid smarter, faster, more robust and more resourceful in regards to self-maintenance and self-healing but no systems thinking and CAS is ever applied to the whole meta-system and its underlying structure. No treatment of the complex interaction and assistantship that may take place among different systems integrating a microgrid is addressed, how these systems can coordinate and cooperate among themselves much like living organs do during metabolic processes in living systems, communicating to and coordinating with each other and with the customer, at each stage of the operation cycle, informing the status of the system along with any other relevant piece of information, such as climatic variables, conditions of the utility grid to which the small microgrid system is connected, and other meaningful/relevant considerations that can influence the meta-system's behavior and enhance systems coupling and assistantship.

3.3. Differences between conventional grids and smart microgrids

In general, conventional grids have a limited capability of monitoring and control; control centers communicate with generation centers, power substations and large consumers; control functions are often operated manually. In contrast, a smart grid is

characterized by a two-way flow of electricity and information and is capable of monitoring everything from power plants to customer preferences to individual appliances. It delivers real-time information and enables the near-instantaneous balance of supply and demand at the device level. It can operate at different scales as long as it is located near the source of energy and near the areas of delivery, ideally used to produce and consume energy locally. It involves changes not only in the technology, but also in the elements such as user practices, regulations, industrial networks, infrastructure and symbolic meaning [161–206,231]. In regards to the latter, and in an effort to further explain the approach being presented here, the major criticism to be made here is that conventional microgrids have limited scope, with a limited capability of monitoring and control, especially over the power supply and energy demand equilibrium requirement when only limited supply is available and no energy storage is present. There is also an excessive preoccupation with net metering and demand response management and little regard for systems dynamics and interactions from a CAS point of view [216–230] in the treatment of varying degrees of complexity and the need for adaptability faced by the meta-system throughout the day. Moreover, there is a need in the topic of grid-tie microgrids without energy storage to explore how a collective effort of systems assisting and cooperating with each other in a “conscious” (awake) manner can better help the operation of the whole meta-system (the system of systems whereby the grid, the homes and the renewable microgrid are all coupled together comprising one single system), particularly with respect to optimal power generation and supply. How they are able of cooperating and assisting one another collectively, much like a living organs would through homeostasis, to reach an efficient equilibrium state. In fact the whole discussion throughout the literature reviewed on the latest state-of-the-art trends and technologies in the microgrid field centers around the idea of making the smart microgrid smarter, treating it like an intelligent living system, a living organism that is “awake”, capable of regulating itself and adaptive to sudden changes. One that is able to communicate at every coupling node with other systems, being able to interact with its environment, assisting one another and being capable of self-organizing, self-healing and overcome chaos when perturbed [80,216–228].

In [81] “A social SCADA approach for a renewable based microgrid—The Huatacondo Project” the smart grid concept is also addressed but in a different way, adding that it is interdisciplinary in nature, comprising a set of technological solutions for electric power system management. Thus a smart grid is understood as the key enabling technology for renewable energy development, electric vehicle adoption, and EE improvements [81]. It represents a vision for a digital optimization of electric power distribution and transmission grids as applied to current operations, enhancing the grid security, and opening up new ways of tapping alternative energy sources. In this case authors focus also on rural and remote communities, but in this case they propose Internet Protocol (IP) on home devices for data monitoring and transmission, thus making it possible for the smart grid to send information back and forth between the distributed electric utility grid and the customers. The authors in [35,81–83] propose a demand response management strategy for a HRES in the context of flexible demand, with significant intermittent generation, e.g. a microgrid with several renewable sources. In this system, the energy demand can shift and be flexible to reduce the peak power demand and also peak shaving or shedding in order to mitigate the system's power fluctuations; however this action requires evaluating the value of lost load for consumers. Emphasis is put on the need for reliable, real-time control and monitoring systems when a high penetration of DG is present. Along a similar line, Palma et al. [81] and [82] talk about an electricity generation system based on diesel-fueled generator in a remote location of Chile where no grid is present. Such system is to be intervened by a technological transformation [81,82], meaning that a more sustainable energy system is to bring changes and challenges to the community as compared to the original conditions, thus requiring resilience on the people's part, and the need to adapt to these changes. The methodology referred to in the paper corresponds to the assessment and intervention stages of the project, developed from November 2009 to February 2011 in Huatacondo, a tiny village of approximately 100 inhabitants in a remote mountainous location in the north of Chile. [81,82]

4. Viewing and managing hybrid renewable energy systems (HRES) as living open systems

Although HRES are open systems, they can have the characteristics of a closed system if a subsystem with the function of monitoring and regulating the power flow is introduced by means of feedback loop between output (consumers) and input (supervisory control which administers the resource allocation) as inputs, the RES cannot be changed but the load may be changed through flexible demand. Thus with a back-up system operating as another energy source (for example a diesel generator plant) the system can be designed as a partial closed-loop feedback system [87,193–197,219–223] allowing control actions to correct the output if necessary.

4.1. Systemic thinking in operational concepts of the sustainable hybrid energy system (SHES)

A systems thinking approach is that which is used for developing models that enable our understanding of events, their apparent randomness, interrelations and the patterns resulting from such events, which at times can constitute a trend; but even more importantly is the understanding of the underlying structure responsible for these patterns and the conditioning factors/drivers acting therein. Particularly, when we seek to analyze a complex phenomenon from a systemic viewpoint, trying to understand what elicits a particular behavior and the outcomes thereafter, we realize that it is only through our understanding of the underlying structure and its dynamics that we will be able to identify the most appropriate leverage points to effect change within the system and produce the desired outcome. Goodman et al. [212] in their book *“Designing a Systems Thinking Intervention”*, give a thorough account of the theoretical and technical foundations behind the discipline, giving various interesting examples of the systems thinking (ST) approach to tackle more mundane, every day problems as well as more complex ones, and explain how to design a ST intervention successfully [212], including identifying and diagramming problems, modeling and testing causal theories, and building control strategies and decision support in complex dynamic systems. Other authors have also contributed significantly to the task of bringing much and important understanding into systems thinking, self-organizing and the co-evolution of interacting dynamic systems such as those already described, offering various insights and methodological schemes for problem solving on scales ranging from the personal to the global [212–224].

Fig. 13 shows the schematic diagram of a potential PV-Wind HRES connected to the grid without energy storage, supplying power to a small community in the form a sustainable block in a rural location of Chile. The meta-controller coordinates and controls de entire system in a distributive manner, and incorporates a novel (technical innovation) element called a *homeostatic regulator* for enabling the (sustainable hybrid energy system) SHES, which

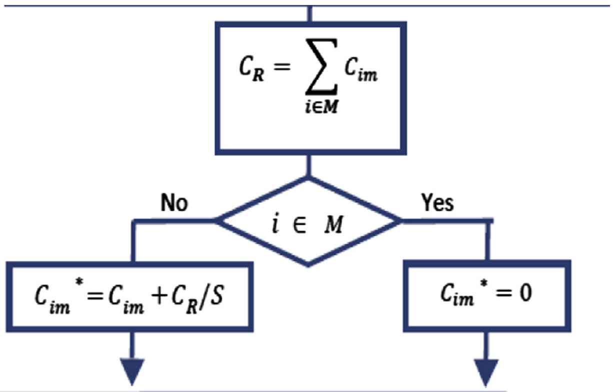

Fig. 13. A portion of the particular criterion already seen is shown above as an illustration.

operates much like the homeostatic regulation (HR) that takes place in the metabolic system of living organisms like humans and animals. Living organisms in general undergo metabolic changes, maintain homeostasis seeking to preserve efficiency and stability in the system, and possess a capacity to react, respond to stimuli, grow, reproduce and adapt to their environment successively for generations. The system's homeostatic regulator is a vital part of the meta-controller, and constitutes the means to regulate energy flow to and from the smart microgrid to the homes and also the energy flow to and from the utility grid. It is in essence an intelligent component that enables the meta-control system of the smart microgrid to manage the energy flow among systems making the system aware of itself in regards to its sustainability. There is power flowing to the AC loads and power exchange between the HRES and the utility grid (dark arrows). Likewise, energy flows from Solar PV panels generating DC electricity going through the meta-controller and through the DC/AC inverter before going into the AC loads (the homes in the sustainable block). The energy also flows from the set of small wind turbine generators, and this AC electrical energy goes through an AC/AC converter to improve the power quality prior to supplying the AC loads. There are communications and control links throughout the system and information is readily made available to home dwellers and to the power utility grid control operator remotely as mentioned earlier.

Looking back at the SHES challenge and the smart microgrid concept discussed earlier, it is reasonable to expect that as energy becomes more available and affordable, it will be consumed more often and in greater quantities. But what happens if the opposite occurs? We would expect consumers to exercise some restraint in energy consumption, just as the human body saves energy when faced with lack of energy and water sources impelled by HR mechanisms. Everyone knows and has experienced this phenomenon in his/her life when facing food and water shortage, the body slows down its metabolism, and one tends automatically to eat less or drink less water. The same thing happens when the body faces cold temperature; it will seek to spend a little energy as possible and save its caloric stock especially when there are no means of getting the body warmer with appropriate clothing or by means of heating the environment one is in. Thus a smart, sustainable supervisory control strategy for HRES must therefore emulate the homeostatic mechanism of open living systems, like those of humans and animals, where the system is aware of its internal functioning and transitioning phases as it interacts with its environment while carrying out its internal processes. For this to occur successfully it is imperative that the system be keenly aware ("awake"), informed at all times of what is happening inside as well as outside of itself, in the changing environment with which it interacts and be able to send and receive information. When the HRES faces scarcity of sunlight for example or when the wind does not blow as strong for the wind turbine generators to operate at rated speed or else when, at some point in time during the day, it senses a shortage of electricity supply or voltage drops (sagging voltage) from the utility electric grid to which it is connected, it immediately reacts upon the new condition with the capabilities that are built into the system. Thus, in such cases control mechanisms sense these changes and act upon them, regulating and self-organizing within the HRES functioning in new ways to accommodate to the new conditions.

Therefore, depending on the nature of the changes that the HRES is facing, the system may oversupply or exert restrain upon itself, coordinating with other systems accordingly and communicating its condition and the causes that triggered it to users inside the homes via a wireless network. At the same time, it works diligently to optimize its operation in such a way as to maximize the energy availability that it is able to extract from other interconnected systems. Thus what is happening here is that the whole meta-system, the system of systems, which comprises the households within the sustainable block, the grid-tie HRES which comprise the smart microgrid which supplies electricity to the homes, and the electric utility grid to which the homes and the smart microgrid are all coupled with, communicating, interacting and assisting each other in real time, and are hence capable to self-regulating, adapting, and coordinating with one another if necessary to achieve the best possible results for the entire meta-system. Once we realize that the HRES may be viewed and managed like a living organism, like humans and animals, which upon uncertain and varying conditions in their environment, immediately change their behavior and adapt in order to adequately face the changes brought upon them. Moreover, nature has it that living systems are self-healing, so they periodically regulate and adapt themselves as needed through homeostasis in order to survive and prolong their lifetime as much as possible. Hence HRES can also be endowed with similar capabilities by means of sensing devices, communication and control to read the environment, the state of the electric utility grid to which it is connected, as well as the loads it supplies. Thus the SHES can be turned into a smart HRES servicing a sustainable load in which the consumers in their homes are an active part of the system which is coupled with the grid. The task then becomes a clear one: to devise the best possible coordination and control strategy to achieve energy sustainability of the meta-system of which the HRES is part.

4.2. Communication systems and data-sensing devices at the core of homeostatic control model

Before going further we wish to stress the need for SHES to communicate relevant information to customers on a continuous basis, as they are the ones to make the decisions on when, how and how much energy to use at any point in time. The SHES is there to satisfy demand based on consumer behavior and the particular criterion being used in the system to make power supply from the microgrid as efficient and sustainable as possible. At the same time, if there is the need for the SHES to respond to an internal event related to the operation and stability of the subsystems that comprise the microgrid, it will act upon it as it is engineered to do so, relying on its built-in capabilities and resources. On the other hand, if an external event occurs, such as sudden variation in RES due to weather conditions or perhaps difficulties in its interconnection with the distribution grid due perhaps to a fault line somewhere or a natural event such as strong winds or a quake, the SHES will respond accordingly as it is expected to do. Here we look at the interaction among the different systems, lower-order systems like the HRES with higher-order systems (due to their degree of complexity) such as the

utility grid and the sustainable block, both of which are connected to it. Thus, the SHES may communicate continuously its overall operational condition and key parameters of the same to the utility grid's control operator and also to customers in their homes. If for example, at some point there is not enough capacity in the microgrid to supply as much power as it is called for, due perhaps to weak/low availability of RES to draw energy from or an internal problem, the SHES will enter immediately in a state of optimized configuration, self-regulating and adapting itself, self-healing if need be, so as to perform its function as adequately and efficiently as possible. If this implies drawing more power supply from the grid, it will do so and communicate it to the customers, reflecting also the change in the price of the electrical energy being consumed at that point. Thus the SHES will act accordingly depending on the circumstances and how they present themselves, yet seeking to endure and extend its operation as much and as best as possible. These various modes of operation that the SHES can enter depending on the circumstances along with the respective causes that triggered such change in operation must be communicated to the customers/users of the system, operating in whatever setting the system may be: a group of homes termed a sustainable block in a rural location somewhere, an emergency shelter, an encampment, a 24-h running health care facility (like those which are much needed especially in rural areas and in short supply still in several regions of Chile), a military outpost or a school to which it supplies power. Therefore, as already stated, the different modes of operation and the different anomalies that may occur therein – whether these are due to internal conditions like a system malfunction or to external occurrences emerging from the environment – like for example a sudden, abrupt weak sunlight irradiation in a clear sunny day of summer, due perhaps to scattered clouds or a spout of coastal fog dropping in, or strong wind gust and rain, all which may be responsible for triggering the system's responses in the form of self-adapting, self-organizing, co-evolving and restraining mechanisms. Indeed if one is to employ a systems thinking and cybernetics [212–224] approach implemented through a HC system strategy for the SHES, one ought to focus on the entire meta-system, considering that these are recursive actions taken by the entire system including the customers/users, all operating as one single system to reach efficient equilibrium and discrete optimality, in order to optimize and prolong the system resources and operability, just like the body of humans and animals do when faced with similar situations.

In Fig. 14, we have the key technology enablers of today's smart microgrid system. The model proposed based on a systems thinking, cybernetics and CAS theory approach aims for a radical detour from the traditional emphasis on technical component integration, component compatibility and larger capacity considerations of today's main stream approach, focused much more on hardware than on people's needs and requirements. Although this process is ongoing with the systems involved undergo continuous changes and experience the need for adaptability as part of the meta-system, such a system is only partially open to explicit human intervention but for the most part it is determined by the structural and organizational capabilities built into the meta-system itself, and how these that matters. This will ultimately determine the success or the failure of the supervisory control strategy being implemented. From this particular perspective, capability building in the meta-system is the capacity to change, to adapt, to self-organize and endure change and adversity; it is essentially an emergent property of CAS that arises from a continuous process of self-organization and adaptation among the systems involved. The term emergence describes how complex systems change and how different capabilities develop continuously within them towards this end. Thus, the supervisory control strategy sought in the present approach seeks to build such capacity and capabilities, manage them optimally and ultimately have the meta-system be able to control emergence successfully and collectively, as a system of systems, consciously “awake” of what is happening at all times inside and outside of it and know how to best handle emergence and co-evolution systemically Fig. 15.

4.3. Systems coupling, coordination and self-adaptation/regulation capabilities of SHES

At the core of the proposed homeostatic control system strategy are the systems coupling, coordination and self-adaptation/regulation capabilities of the SHES which the system can exhibit whenever there is need for the system to act. The particular contribution of this paper lies in highlighting and underpinning the basic elements behind a possible supervisory control strategy for grid-connected sustainable hybrid energy systems (SHES) without energy storage, in a small smart microgrid configuration, employing available communication systems, microprocessor-based control using set-points to trigger responses from the different systems and sub-systems involved, employing data-sensing devices to activate such control responses. The SHES will be used to supply electricity to a group of homes in a

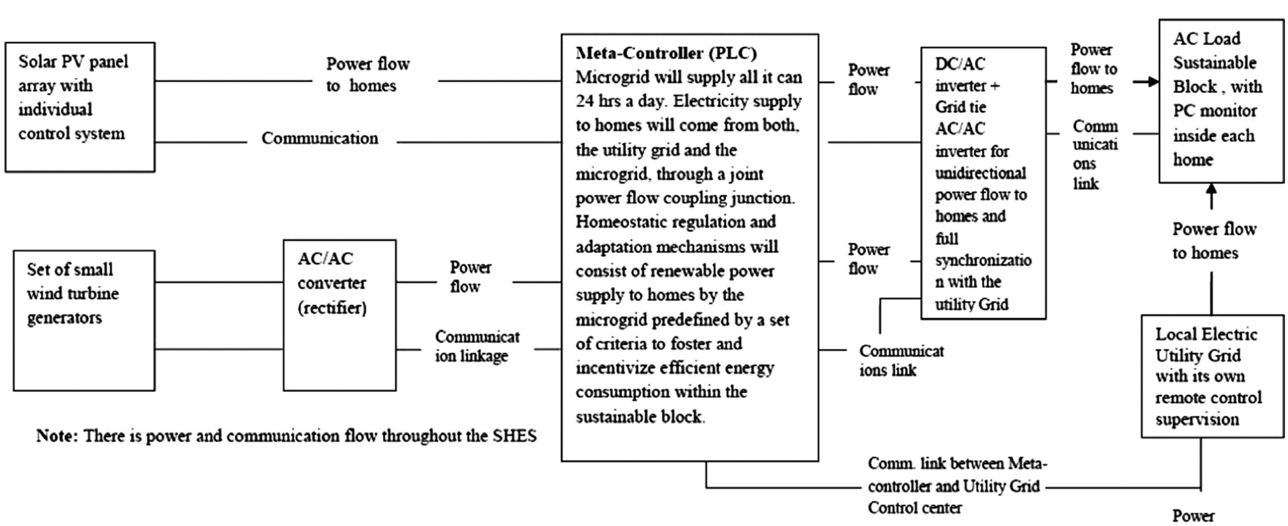

Fig. 14. The schematic diagram of a potential PV-Wind HRES connected to the grid without energy storage.

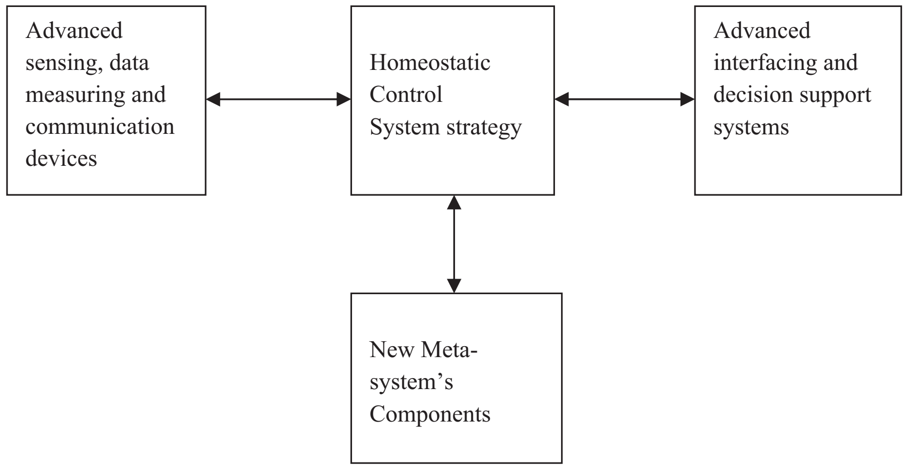

Fig. 15. Technical diagram of key enabling systems comprising a smart microgrid system and interactions therein.

sustainable block especially designed for applications in rural and remote communities of rather low population density, like those present in large numbers in Chile and in South American. The proposed supervisory control system will monitor the group of homes that are connected to both the local electric distribution grid and to the smart microgrid that supplies clean energy to them. The microgrid will be connected via internet protocol (IP) communication network to the utility grid control operator. The grid control operator will monitor the microgrid and know at all times the exact amount of electric power that is being produced by the HRES along with all the energy management and other relevant parameters. Thus the operator will be able to take action if the need should arise, calling for remote intervention and communicate this to the users. Likewise, the homes in the sustainable block will be located near the microgrid and every home will have sensors in its electrical distribution or gang junction box that will allow the microgrid to read the electricity consumption of each home during a 24 h period all throughout the day and also identify the different sources and magnitudes of power consumption (appliances, lighting, heating, etc) utilized by the dwellers. Hence the microgrid control system will be able to measure at each instant of the day the electric power demand from the home and adjust its power supply accordingly, thus being able to divert more electric power to those homes that demand more while others demand less. At some point during the day, and especially during periods of high energy demand, the microgrid's power supply will not be enough to meet the homes electricity demand even if kept moderate and therefore the microgrid supervisory control will automatically switch over to the electric power distribution grid. Later, once the electricity consumption of the homes decreases to a manageable level, one which is within the power supply range of the microgrid's installed capacity, the microgrid's supervisory control – which is monitoring at all times the energy demand of the homes – will send the signal to the home's electrical supply network controller (a programmable logic controller or PLC), signaling that it is taking over, thus switching the homes electric supply back to the microgrid entirely or to a larger extent than it was possible before Table 1.

Furthermore, *smart metering* is a fundamental part of a grid-connected smart microgrid for rural and remote communities where the electricity distribution network is already present. This way if the law permits it, the homes will be able to sell the excess of electric power produced by the microgrid to the grid, once the demand in the home is low and there is a surplus coming from the microgrid's supply. Such excess power can be injected back into the local grid instead of going to waste on a dump load. This otherwise wasted energy could very well be used in alternative processes with some combined heat-and-power (CHP) application; for instance space heating and cooling or providing heat flow for some industrial process. Similarly it can be used to supply power to an additional load such as a groundwater pump as it is done in several remote locations without adequate water supply infrastructure. As mentioned before, this application considered in the context of the sustainable blocks calls for activation sensors, controllers and actuators installed in the home's gang junction box and may also be connected to significant loads in the home, in order to manage the electricity needs of the home more efficiently. At the same time, the system will inform the dwellers through a display monitor the capacity of the microgrid supply at all times and the power consumption of each home so consumers know how much power is being demanded versus how much is available for consumption from the microgrid. Notwithstanding the fact that the local grid will always be present as a back-up system and readily accessible, consumers are being incentivized and conditioned by the particular power supply management criterion being utilized to be thrifty, energy efficient and sustainable in their energy use. This may be possible for example by means of a PC monitor or similar device installed in every house, much like the ones used by any smart home system today, which shows the control actions being taken by the system and displays the control commands for access in case the user wishes to intervene the system control manually. Thus the smart home's controller is connected to every load in the home and uses a local communications network (e.g. LAN) that connects the home with the microgrid and eventually with the utility operator's control center to advice of the situation of each home. Here it is pertinent to quote Branlat et al. [228] in their paper *"How do systems manage their adaptive capacity to successfully handle disruptions? A resilience engineering perspective"*, when they ask: "what happens when new demands arise as a result of changes in the environment or in the system itself. As a result of these points, we define resilience as fundamentally anticipatory, and related to the capacity to handle the next disruption. In short, the resilience of a system corresponds to its adaptive capacity tuned to the future" [228].

The key to understanding the usefulness of the proposed approach lies in the idea of handling emergence and disruptions in a collective, coordinated and conscious effort; not a mechanical, reductionist and deterministic one decided by a device. This view can help to better understand systems capability building and management more effectively, aiming for more capable, smarter and more resilient microgrid system as a capable adaptive meta-

system integrated with other systems and managing the adaptative and self-organizing capacities and capabilities of the systems that comprise it so as to overcome adverse conditions. A meta-system is a system about other systems – a system of systems – such as the constitution of a nation. Lotka [232] once said: "Systems prevail that develop designs that maximize the flow of useful energy" [232] in regards to how open systems manage to use feedback mechanism and an array of adaptive responses, and constantly adapt and change in the face of new circumstances (or disruptions) in order to sustain themselves, maximizing their useful energy, and thus prolonging their effective operability. (Fig. 16)

Above it is shown a model diagram of a solar PV array and a set of vertical wind generators for residential DG projects. The *homeostatic regulator* is built into the supervisory control system of the grid-connected microgrid. It is a piece of technology comprised of both hardware and software, which incorporates an algorithm implemented therein which operates the coordination and control of the meta-system's power supply subject to certain specific criteria based on EE, thriftiness and energy sustainability. Such criteria may change according to specific location conditions and the RES of the site where the system is to be deployed. The specific criterion to be employed could be more generic at first as a base template for supervisory control of such systems but depending on the users and the specific location, it should be tailored to the characteristics of the rural community to be serviced. The homeostatic regulator is designed to act much like a (homeostatic regulation) HR mechanism operating in the metabolic system of living organisms. Living organisms in general undergo metabolic changes, maintain homeostasis seeking equilibrium between energy intake and expenditure, and also possess a capacity to react, respond to stimuli, self-organize, adapt, grow and reproduce. Such HR mechanisms and living systems characteristics have inspired the present HC model with a supervisory control strategy with clear economic and social incentives that seeks to maintain homeostasis and condition energy users to be thrifty and energy efficient is envisaged in the current model for residential power distribution services. (Fig. 17)

Finally, the power consumption of the AC loads is also expected to vary throughout the day. Thus it is important that the microgrid "knows" of this changes and is aware of the varying electricity needs of the homes, as well as the quality of power is supplying, in order to proactively and efficiently respond to these changes in order to fulfill customer requirements effectively and efficiently, coordinating its operation with the utility grid to satisfy demand and keep the energy flow soft and smooth, seamlessly circulating from the microgrid to the sustainable block. The meta-controller will be able to act and respond to interruptions or disruptions being provoked by internal or external phenomena that may occur all of a sudden, adapting the HRES operation to these changes. For example, should the DC/AC inverter fail/break-down, the meta-controller will continue to operate with the wind turbine generators only; or vice versa, should the wind turbines AC/AC power converter break-down at any point, preventing the flow of electrical energy to continue operating properly, the meta-controller will adapt and self-reorganize appropriately to continue operating with the solar PV panels only. In all these cases, much less electric power will be able to flow to the homes due to these disruptions or adverse conditions. In such cases, the meta-controller will determine when the microgrid shall draw the necessary amount of electric power from the utility grid to provide for the deficit. On the other hand, there will be times during the day when the microgrid is providing electricity in excess of what's being consumed by the loads. In these cases, as already seen, one could expect such excess in electrical energy to be used by the grid or by alternative processes. Thus, if smart-metering can be implemented and a deal be worked out with the local power utility, the sustainable block (the homes) could sell this unused or excess electricity back to the utility grid and with this, get a discount on their monthly electric bill.

5. Discussion

Back in the late 1970s when Schweppe introduced HC the reality of the world's energy market was quite different than it is today, and the threat of global warming was non-existent. Oil resources estimates and price of fossil fuels were also different than they are today. Unless we move forward with the right regulatory framework, technology issues and economic incentives for customers and suppliers of DG systems in general and HRES in particular, operating as smart microgrids, things will not change substantially in the direction we need them to. This is especially true for developing countries like Chile, with a very high price of

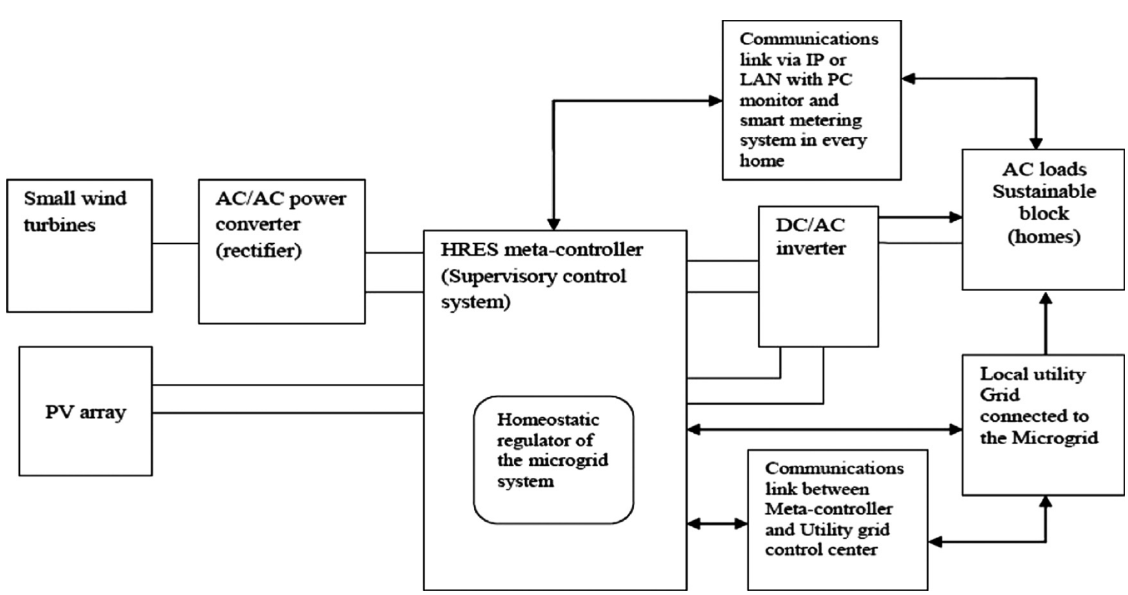

Fig. 16. Model diagram of grid-connected HRES comprising a smart microgrid without energy storage.

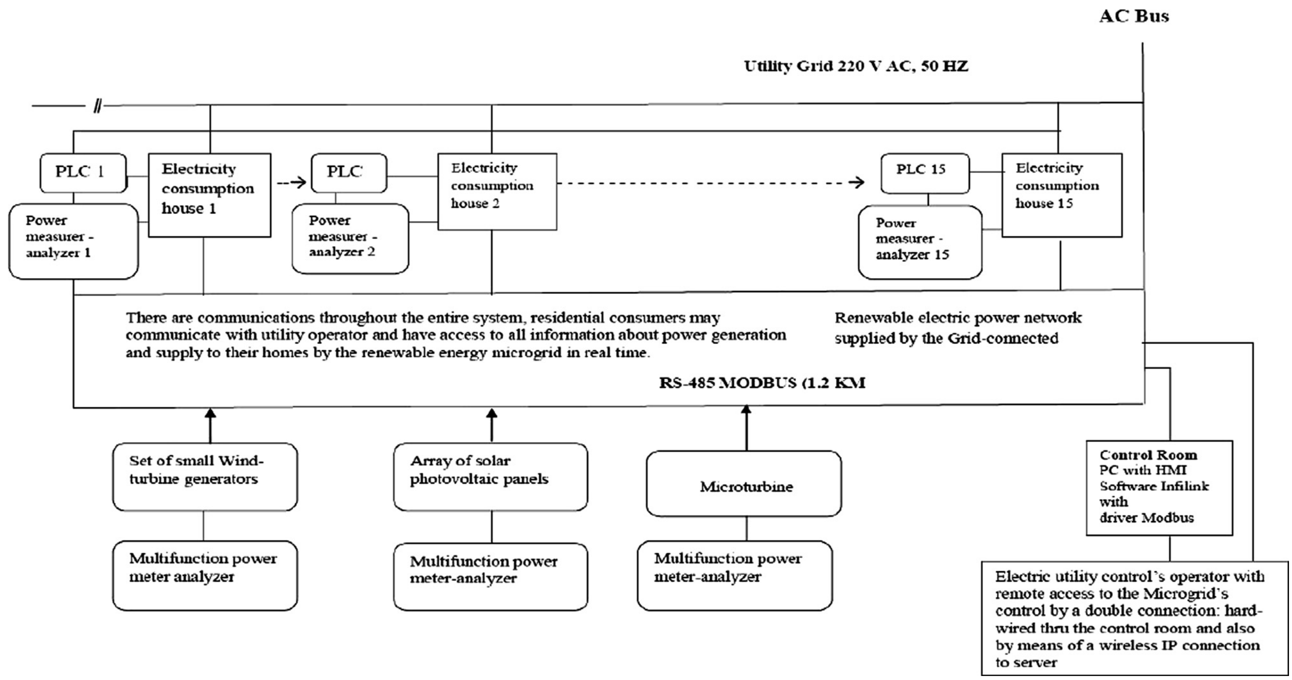

Fig. 17. A possible configuration of the smart microgrid supplying power to a sustainable block of 15 homes.

electricity is paid when compared to other regions of the world. This is also important in order to have all the relevant players actively participate and make their share of commitments to advance in the clean energy crusade. In Chile, a country where the economic growth is still very much tied to energy consumption, and where the electric power generation and distribution sectors are heavily concentrated, the energy matrix is quite centralized in spite of some efforts in the energy policy agenda towards greater decentralization and diversification. At the pace that new electric power generation initiatives and projects are moving, with heavy environmental requirements, new local and national regulatory prerequisites and costly technical and socio-economic studies being required, the uphill road towards new conventional power developments is slowing down future growth. All this amid growing societal scrutiny over this issue, aimed at safeguarding the country's ecological and environmental equilibrium for future generations, and where the green activists and environmentalists are more present today than ever before. These groups play a pivotal role in the way society is reacting towards new energy projects and are making their voice heard in the political arena as well with a very respectful percentage of voters. Under such scenario, a country like Chile which aspires to grow significantly over the next decade to reach developed nation status, will not be able to keep the energy ship afloat at pace with the economic growth agenda, and will have to face dire consequences in the not so distant future. Thus the need to advance in decentralization and diversification of the energy matrix and to make the most of new RET and DG projects in the form of mini and microgrids to stay the course towards greater change and integration with the current electric power infrastructure. This can be achieved by devising new ways and means to use existing technology to advance this crusade. Such is the necessity that Chile faces today; one that stands unequivocally clear and must be aided and supported by adequate regulation, technological innovation and economic policies and incentives.

Likewise, the technology in communications and control systems is far more advanced today than it was back in 1979 and early 1980s when Schweppe introduced HC in electric power systems, while the prices of fuel and electricity keep going up, and with them food and other basic necessities, a reality much felt in Chile in particular, hurting especially the poor and middle classes everywhere. Thus it makes perfect sense in today's world to advance in ways that can foster and elicit the growth of sustainable hybrid energy systems. On the other hand EE has yet to see the light of day and achieve its true potential especially in Latin America where Chile is a clear and present example of this in the region. Therefore we believe that coordination and control strategies that can aid this transformation are to be embraced and implemented. The development and implementation of homeostatic control for hybrid electric power systems in the mini and micro-generation sector is one of them and can have a major impact on the integration of DG and RET employing grid-tie HRES especially in the perspective of governments and small rural communities alike. It should also prove to be an important driver and enabler of EE and the advancement of the energy sustainability agenda worldwide as it seeks to change not only the way grid-connected HRES operate and interact with the current utility grids infrastructure but also the electricity consumption habits of consumers, particularly residential consumers in rural communities, making them active participants and game changers in the energy marketplace. Residential consumers and small businesses in particular, should see their costs go down as they learn to be thrifty, efficient and sustainability-conscious in their energy consumption, in a way that makes it possible for new alternatives in power generation and distribution to exist and enter the marketplace. The large consumers will also have benefits as energy demand should become more moderate and come down with the appropriate incentives so that load shedding does not have to be single-sided and imposed on consumers by the utilities at will. EE and overall systems sustainability depend on and will greatly benefit from homeostatic regulation and control of grid-connected HRES. It makes sense to install stand-alone systems where there is no grid, and invest heavily on large energy storage devices where it is appropriate and economically sound to do so, but in most places there is an important electric power infrastructure already in place with which the RET and DG in general should integrate and fully interact with to take advantage of economies of scale. Thus the words of F. C. Schweppe and his group at MIT back in

1981 are just as valid today as they were back then, when they said: "it is important to have a close interaction between customers and the utility, it is equally important for customers to make independent decisions. It is more efficient for a customer to make the decision to reschedule or even to shed load than it is for an external source, such as an electric utility controller, to make the decision to manage or shed customer load. Industrial customers are far more able to judge the value of electricity to their processes at any given point in time than is the utility controller who has little, if any, information concerning the process. From the utility's point of view, it is important not to be forced into the politically dangerous position of having to play the "big brother" who decides how and when customers are going to use their processes, appliances, or other usage devices. Under Homeostatic Control the utility does not "cross the meter line" and the customer retains complete freedom of decision making." Schweppe et al. [176–178,180]

6. Concluding remarks

"The complexity of systems creates new opportunities, but also new challenges, especially in the form of increasing scope and side effects due to wider networks of interdependencies. A resilient system therefore needs to be able to deploy new ways of functioning" [228].

In this paper a new approach for the understanding and operation of grid-connected HRES has been presented based on systems thinking and cybernetics [212–224]. Such approach explores the energy sustainability concept from an operational and technical standpoint rather than from more traditional perspectives. The paper introduces a theoretical model for implementing supervisory control strategies for grid-interactive HRES employing the smart microgrid concept which has its foundations on homeostatic control (HC). The model seeks to analyze HRES as CAS that can learn and evolve towards sustainable hybrid energy systems (SHES). It is based on an effort to integrate NCRE through DG projects in rural and remote communities, particularly in countries like Chile where such communities abound. Thus in this CAS approach one may distinguish a complex set of relations and fluid interactions amongst the different systems comprising the meta-system, and where coordination and control functions operate, along with self-organizing and self-adapting mechanisms akin to homeostasis in humans and animals. From this perspective, the task of a control design and capability development strategy of such a system is closer to complex system adaptation while interacting with other systems, requiring collective coordination and self-sustenance. This model stands in sharp contrast to the conventional topics of component integration, machine building, systems compatibility and capacity concerns that are common in the literature dealing with HRES and microgrids today. Such is the traditional approach which largely dominates the discussion of the current focus in the literature; one which is centered far more on purely technological aspects and less on the complexity of a human-machine interface. It is found also that there is excessive preoccupation with demand response management and little regard for systems dynamics, interdependencies and interactions from a CAS analysis point of view in the treatment of varying degrees of complexity faced by all the systems involved: the renewable microgrid, the grid with which it is tied and operating in parallel, and the users who consume energy. Thus there is a need for ongoing adaptability faced by the meta-system throughout the day. Moreover, an effort is needed to go beyond component integration and compatibility, and to focus rather on just how such a collective effort of systems (of which the utility grid and the users in their homes are a vital part) assisting and cooperating with each other in a "conscious" (awake), active manner, can make the whole system more capable and resilient. A well coordinated and collective effort, that can better help the operation of the smart microgrid as a meta-system, a smart system of systems, particularly with respect to optimal power generation and supply. In fact the whole discussion throughout the literature review of the state-of-the-art in smart microgrid lends support to the proposed approach for the coordination and control of HRES, where the relevant discussion centers around the idea of making the smart microgrid smarter, treating it like an intelligent complex living system, and being capable of self-healing when perturbed [228] In essence it is how these capabilities built into the meta-system are used that will ultimately determine the success of the coordination and control strategy. From this particular perspective, capability development of such a system is the capacity to react, to change, to adapt; it is essentially an emergent property of systems that arises from a continuous process of self-organization, interactions and adaptation among the different systems involved. The term emergence describes how complex systems change and how different capabilities develop within them. Thus, the coordination and control strategy sought in the present approach seeks to build such capabilities in the meta-system, manage them optimally and ultimately, have the meta-system be able of controlling emergence successfully and collectively, as a system of systems, consciously "awake" of what is happening at all times. As a result, the present model suggests that it is possible to do both: to instill EE and thriftiness in the target community where the project is to be implemented as well as to instill higher flexibility and stability in the system in order to reconcile energy demand response management and power supply management strategies to create true sustainable hybrid energy systems.

Future trends in smart microgrid operation, especially the grid-connected type, should focus more on the issues discussed in this paper, realizing that SHES can be intelligent systems behaving like living systems, which are part of higher-order systems like the grid and the sustainable block, a new concept introduced here. Thus SHES are capable of exhibiting intelligent interactions with such systems when coupled to the local electric distribution network (the grid), and capable of bringing additional benefits to consumers and to the electric power generation system as a whole in spite of the absence of energy storage devices.

References

[1] Burch, GD., Hybrid renewable energy systems, hybrid power systems manager, office of power technologies, US Department of Energy, Golden, CO, USA; 2001.

[2] Lund H. Renewable energy systems: the choice and modeling of 100% renewable solutions, AP academic press is an imprint of ©. Elsevier Inc; 2010. All rights reserved.

[3] Lund H, Duić N, Krajačić G, da Graca Carvalho M. Two energy system analysis models: a comparison of methodologies and results. Energy 2007;32 (6):948–54 Third Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems.

[4] Lund H. Renewable energy strategies for sustainable development. Energy 2007;32(6):912–9.

[5] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems—a market operation based approach and understanding. Energy 2012.

[6] HYBRID MINI-GRIDS FOR RURAL ELECTRIFICATION: LESSONS LEARNED, Alliance for Rural Electrification: Publications; 〈http:/www.ruralelec.org/6.0.html〉.

[7] The Alliance for Rural Electrification (ARE) 〈http:/www.ruralelec.org/〉, Hybrid power systems based on renewable energies: a suitable and cost-competitive solution for rural electrification. In: SAFT to deploy state-of-the-art lithium-ion energy storage systems for MILLENER Smart Grid Project (2011-July-29); 2011.

[8] Guerrero JM, Blaabjerg F, Zhelev T, Hemmes K, Monmasson E, Jemei S, et al. Distributed generation: toward a new energy paradigm. IEEE Industrial Electronics Magazine 2010;4(1):52–64.

[9] Rabiee A, Khorramdel H, Aghaei J. A review of energy storage systems in microgrids with wind turbines. Renewable and Sustainable Energy Reviews 2013;18:316–26.
[10] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renewable and Sustainable Energy Reviews 2008;12 (5):1221–50 2008.
[11] Zamora R, Srivastava AK. Controls for microgrids with storage: review, challenges, and research needs. Renewable and Sustainable Energy Reviews 2010;14(7):2009–18.
[12] Pinto F. Renewable energy for electricity generation—renewable electrification of the Galapagos Islands. Ecuador: Global Environment Facility, United Nations Development Programme (UNDP); 2001.
[13] Kaldellis JK, Zafirakis D, Kavadias K. Techno-economic comparison of energy storage systems for island autonomous electrical networks. Renewable and Sustainable Energy Reviews 2009;13(2):378–92.
[14] Moloney S, Horne RE, Fien J. Transitioning to low carbon communities-from behaviour change to systemic change: lessons from Australia. Energy Policy 2009;38(12):7614–23.
[15] Magnoni, S; Bassi, AM., 2009. Creating synergies from renewable energy investments: a community success story from Lolland, Denmark by Millennium Institute. In: Papers by Millennium Silvia Magnoni and Andrea M. Bassi Source Energies, 2, 1151-1169.
[16] Afzala A, Mohibullah M, Virendra KS. Optimal hybrid renewable energy systems for energy security: a comparative study. International Journal of Sustainable Energy 2010;29(1) (available at Taylor Francis Online and EBSCO).
[17] Akella AK, Sharma MP, Saini Kralova RPI, Sjöblom J. Optimum utilization of renewable energy sources in a remote area. Renewable and Sustainable Energy Reviews 2007;11:894–908;
Akella, AK Sharma, MP Saini Kralova RPI, Sjöblom J.Biofuels-renewable energy sources: a review. Journal of Dispersion Science and Technology, 31(3):409–425.
[18] Chen F, Duic N, Alves LM, da Graca Carvalho Maria. Renewislands—renewable energy solutions for islands. Renewable and Sustainable Energy Reviews 2007;11:1888–902. ⟨http:/www.europeanislands.net⟩.
[19] Key World Energy Statistics 2010 ⟨http:/www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf⟩.
[20] Bhikabhai, Y. Hybrid power systems and their potential in the Pacific islands. In: SOPAC miscellaneous report 40. Community Lifelines Programme, SOPAC Secretariat; 2005, ⟨http:/www.sopac.int/data/virlib/MR/MR0406.pdf⟩.
[21] Jaramillo-Nieves, L Del Río, P. Contribution of renewable energy sources to the sustainable development of Islands: an overview of the literature and a research agenda (2010); Sustainability 2010, 2, 783–811; Sustainability ⟨http://www.mdpi.com/journal/sustainability⟩: Sustainability—Open Access Journal.
[22] Gischler, C; Janson, N.; Perspectives for distributed generation with renewable energy in Latin America and the Caribbean: analysis of case studies for Jamaica, Barbados, Mexico, and Chile, Inter-American Development Bank Capital Markets and Financial Institutions Division. In: Discussion Paper no. IDB-DP-208; November 2011.
[23] Deshmukh MK, Deshmukh SS. Modeling of hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 2008;12(1):235–49.
[24] Woona WL, Zeineldina H, Madnick S. Bibliometric analysis of distributed generation. Technological Forecasting and Social Change 2011;78(3):408–20.
[25] Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning—a review. Renewable and Sustainable Energy Reviews 2004;8(4):365–81.
[26] Løken E. Use of multicriteria decision analysis methods for energy planning problems. Renewable and Sustainable Energy Reviews 2007;11(7):1584–95.
[27] Nema P, Nema RK, Rangnekar S. A current and future state of art development of hybrid energy system using wind and PV-solar: a review. Renewable and Sustainable Energy Reviews 2009;13(8):2096–103.
[28] Liserre Marco, Sauter Thilo, Hung John Y. Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics. IEEE Industrial Electronics Magazine 2010;4(1):18–37.
[29] Das A, Balakrishnan V. Sustainable energy future via grid interactive operation of spv system at isolated remote islands. Renewable and Sustainable Energy Reviews 2012;16(7):5430–42.
[30] Vale Z., et al. Distributed energy resources management with cyber-physical SCADA in the context of future smart grids. In: En MELECON 2010-2010 15th IEEE Mediterranean electrotechnical conference. IEEE; 2010. p 431–436.
[31] MD Ilić, L. Xie, UA Khan, JMF. Moura. Modeling future cyber-physical energy systems. In: IEEE power and energy society general meeting Pittsburgh, PA; July, 2008.
[32] Vale Z, Morais H, Faria P, Ramos C. Distribution system operation supported by contextual energy resource management based on intelligent SCADA. Renewable Energy 2013;52:143–53.
[33] Park SJ, Kang BB, Yoon JP, Cha 1S, Lim JY. A study on the stand-alone operating of photovoltaic-wind power hybrid generation system. In: 35th annual IEEE power electronics specialists conference; 2004. p. 2095–2099.
[34] Valenciaga F, Puleston PF. Supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy. IEEE Transactions on Energy Conversion 2005;20(2):398–440.
[35] Alvial-Palavicino C, Garrido-Echeverría N, Jiménez-Estévez G, Reyes L, Palma-Behnke R. A methodology for community engagement in the introduction of renewable based smart microgrid. Energy for Sustainable Development 2011;15(3):314–23.
[36] Akorede MF, Hizam H, Pouresmaeil E. Distributed energy resources and benefits to the environment. Renewable and Sustainable Energy Reviews 2010;14(2):724–34.
[37] Climate Technology Initiative (CTI)—Industry Joint Seminar on Technology Diffusion in Latin America and Caribbean (2009), CASE STUDY: Remote Area Power Supply Project – Loreto – Peru. Published by the International Institute for Sustainable Development (IISD) ⟨http:/www.iisd.ca/process/climate_atm.htm⟩.
[38] Ashok S. Optimised model for community-based hybrid energy system. Renewable Energy 2007;32(7):1155–64.
[39] Chicco G, Mancarella P. Distributed multi-generation: a comprehensive view. Renewable and Sustainable Energy Reviews 2009;13(3):535–51.
[40] Moon SJ, Kang SH, Nam SR. Power-sharing method of multiple distributed generators considering control modes and configurations of a microgrid. IEEE Transactions on Power Delivery 2010;25(3):2007–16.
[41] Jiayi H, Chuanwen J, Rong X. A review on distributed energy resources and MicroGrid. Renewable and Sustainable Energy Reviews 2008;12(9):2472–83.
[42] Basak P, Chowdhury S, Halder nee Dey S, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renewable and Sustainable Energy Reviews 2012.
[43] Pedrasa MAA, Spooner TD, Macgill IF. Coordinated scheduling of residential distributed energy resources to optimize smart home energy services. IEEE Transactions on Smart Grid 2010;1(2):134–43.
[44] Timbus A, Larsson M, Yuen C. Active management of distributed energy resources using standardized communications and modern information technologies. Industrial Electronics, IEEE 2009;56(10):4029–37.
[45] Shuai L, Elizondo MA, Samaan N, Kalsi K, Mayhorn E, Ruisheng D, et al. Control strategies for distributed energy resources to maximize the use of wind power in rural microgrids. IEEE Power & Energy Society 2011:1–8.
[46] Vale ZA, Morais H, Khodr H. (2010). Intelligent multi-player smart grid management considering distributed energy resources and demand response. In: Power and energy society general meeting, IEEE; 2010. p. 1–7.
[47] Nyeng P, Ostergaard J. Information and communications systems for control by-price of distributed energy resources and flexible demand. IEEE Transactions on Smart Grid 2011;2(2):334e41.
[48] Labini MS, Delvecchio G, Guerra M, Lofrumento C, Neri F. A study for optimizing the management strategies of a hybrid photovoltaic-diesel power generation system. In: Proceedings of international conference on renewable energies and power quality (ICREPQ) '04, Barcelona; 2004.
[49] Patidar RD, Singh SP. Active and reactive power control and quality management in DG-grid interfaced systems. ARPN Journal of Engineering and Applied Sciences 2009;4(3).
[50] Paiva JEMS, Carvalho AS. An integrated hybrid power system based on renewable energy sources with electric wind MPPT. In: IECON 2010—36th annual conference on IEEE industrial electronics society; 7–10 Nov 2010. p. 2981–2987.
[51] Pepermans J, Driesen J, Haeseldonckx D, Belmans R, D'haeseleer W. Distributed generation: definition benefits, and issues. Energy Policy 2005;33: 787–98.
[52] Coster EJ, Myrzik JMA, Kruimer B, Kling WL. Integration issues of distributed generation in distribution grids. Proceedings of the IEEE 2011;99(1): 28–39.
[53] Ackermann T. Distributed resources and re-regulated electricity markets. Electric Power Systems Research 2007;77(9):1148–59.
[54] Eltawil MA, Zhao Z. Grid-connected photovoltaic power systems: technical and potential problems—a review. Renewable and Sustainable Energy Reviews 2010;14(1):112–29.
[55] Agüero J, Rodríguez F, Giménez A. Energy management based on productiveness concept. Renewable and Sustainable Energy Reviews 2013;22: 92–100.
[56] Ning, L, Hammerstrom DJ. Design Considerations for frequency responsive Grid Friendly™ appliances. In: Proceedings of the IEEE PES transmission and distribution conference and exhibition, 2005/2006, Dallas, MT, USA; 2006. p. 647–652. http://dx.doi.org/10.1109/TDC.2006.1668573.
[57] Berger AW, Schweppe FC. Real time pricing to assist in load frequency control. IEEE Transactions on Power Systems 1989;4(3):920–6. http://dx.doi.org/10.1109/59.32580.
[58] Jay D, Swarup KS. Frequency restoration using dynamic demand control under smart grid environment. IEEE PES Innovative Smart Grid 2011;1:311–5. , http://dx.doi.org/10.1109/ISET-India.2011.6145408.
[59] Molina-Garcıa A, Bouffard F, Kirschen DS. Decentralized demand-side contribution to primary frequency control. IEEE Transactions on Power Systems 2011;26(1):411–9.
[60] Donnelly M, Harvey D, Munson R, Trudnowski D. Frequency and stability control using decentralized intelligent loads: benefits and pitfalls. IEEE Power & Energy Society 2010;1:1–6.
[61] Xu Z, Ostergaard J, Togeby M. Demand as frequency controlled reserve. IEEE Transactions on Power Systems 2011;26(3):1062–71. http://dx.doi.org/10.1109/TPWRS.2010.2080293.
[62] Samarakoon K, Ekanayake J. Demand side primary frequency response support through smart meter control. In: Proceedings of the 44th international universities power engineering conference. Glasgow, England; 2009. p 1–5.
[63] Black JW Ilic. M. Demand-based frequency control for distributed generation. In Power Engineering Society summer meeting; 2002. IEEE, vol. 1, p. 427–432.

[64] Ilic MD, Popli N, Joo JY, Hou Y. 2011. A possible engineering and economic framework for implementing demand side participation in frequency regulation at value. In: Power and energy society general meeting; 2011. IEEE, p. 1–7.
[65] Donnelly M, Harvey D, Munson R, Trudnowski D. Frequency and stability control using decentralized intelligent loads: benefits and pitfalls. IEEE Power & Energy Society 2010;1:1–6. http://dx.doi.org/10.1109/PES.2010.5589835.
[66] Jay D, Swarup KS. Frequency restoration using dynamic demand control under smart grid environment. IEEE PES Innovative Smart Grid 2011;1:311–5. http://dx.doi.org/10.1109/ISET-India.2011.6145408.
[67] Constantopoulos P, Schweppe FC, Larson RC. ESTIA: a real-time consumer control scheme for space conditioning usage under spot electricity pricing. Computers and Operations Research 1991;18(8):751–6.
[68] Ramchurn, S, Vytelingum, P, Rogers, A, Jennings, N. Agent-based control for decentralised demand side management in the smart grid. In: The tenth international conference on autonomous agents and multiagent systems (AAMAS 2011b), Taipei, Taiwan; 02–06 May 2011. p. 5–12.
[69] Pina A, Silva C, Ferrao P. The impact of demand side management strategies in the penetration of renewable electricity. Energy 2012;41(1):128–37.
[70] O'Driscoll M. FERC report marks significant progress in demand response, Advanced metering; 2008. From 〈http:/www.ferc.gov/news/news-releases/2008/2008-4/12-29-08.asp〉.
[71] Asif M, Muneer T. Energy supply, its demand and security issues for developed and emerging economies. Renewable and Sustainable Energy Reviews 2007;11(7):1388–413.
[72] Diana G, Govender P. Demand side management: a case study of a tertiary institution. In: Proceedings of the international conference on electric utility deregulation and restructuring and power technologies. Lai LL (editor). London, England; 2000. p. 419–24. http://dx.doi.org/10.1109/DRPT.2000.855701.
[73] Faria P, Vale Z, Soares J, Ferreira J. Demand response management in power systems using a particle swarm optimization approach. IEEE Intelligent Systems, http://dx.doi.org/10.1109/MIS.2011.35, in press.
[74] Palensky P, Dietrich D. Demand side management: demand response, intelligent energy systems, and smart loads. IEEE Transactions on Industrial Informatics 2011;7(3):381–8. http://dx.doi.org/10.1109/TII.2011.2158841.
[75] Hamidi V, Li F, Robinson F. The effect of responsive demand in domestic sector on power system operation in the networks with high penetration of renewables. In: Energy, S., ed. General meeting of the IEEE Power and Energy Society, Pittsburgh, PA, USA; 20–24 July 2008.
[76] Shao S, Pipattanasomporn M, Rahman S. Demand response as a load shaping tool in an intelligent grid with electric vehicles. IEEE Transactions on Smart Grids 2011;2(4):624–31. http://dx.doi.org/10.1109/TSG.2011.2164583.
[77] Albadi MH, El-Saadany EF. A summary of demand response in electricity markets. Electric Power Systems Research 2008;78(11):1989–96.
[78] Black JW. 2005. Integrating demand into the U.S. electric power system: technical, economic, and regulatory frameworks for responsive load. PhD thesis. MIT.
[79] Faruqui A, Sergici S. The power of experimentation: new evidence on residential demand response. San Francisco: The Brattle Group; 2008.
[80] Xin H, Qu Z, Seuss J, Maknouninejad A. A self-organizing strategy for power flow control of photovoltaic generators in a distribution network. IEEE Transactions on Power Systems 2011:1462–73 ..
[81] Palma-Behnke R, Ortiz D, Reyes L, Jimenez-Estevez G, Garrido N. Social SCADA and demand response for sustainable isolated microgrids. In: IEEE PES innovative smart grid technologies conference; 2012. 〈http://dx.doi.org/10.1109/ISGT.2012.6175756〉.
[82] Palma-Behnke, R, Ortiz, D, Reyes, L, Jimenez-Estevez, G, Garrido, N. A social SCADA approach for a renewable based microgrid—the Huatacondo project. In: Power and energy society general meeting; 2011. IEEE, p. 1–7.
[83] Palma-Behnke, R, Benavides, C, Aranda, E, Llanos, J, Saez, D. Energy management system for a renewable based microgrid with a demand side management mechanism. In: Computational intelligence applications in smart grid (CIASG), 2011 IEEE symposium on; 2011. p 1–8.
[84] Hong J. The development, implementation, and application of demand side management and control (DSMþc) algorithm for integrating micro-generation system within built environment, in energy systems unit, department of mechanical engineering. Glasgow: University of Strathclyde; 273.
[85] Blasques LCM, Pinho JT. Metering systems and demand-side management models applied to hybrid renewable energy systems in micro-grid configuration. Energy Policy 2012;45(0):721–9.
[86] Kelly A, Marvin S. Demand-side management in the electricity sector: implications for town planning in the UK. Land Use Policy 1995;12(3):205–21.
[87] Seligman C, Darley JM. Feedback as a means of decreasing residential energy consumption. Journal of Applied Psychology 1977;62(4):363.
[88] Joo J-Y, Ilić M. A multi-layered adaptive load management (ALM) system: information exchange between market participants for efficient and reliable energy use. In: IEEE PES transmission and distribution conference; 2010.
[89] Gomaa S, Seoud Aboul KA, Kheiralla HN. Design and analysis of photovoltaic and wind energy hybrid systems in Alexandria, Egypt. Renewable Energy 1995;6(5–6):643–7.
[90] Hiremath R, Shikha S, Ravindranath N. Decentralized energy planning; modeling and application—a review. Renewable and Sustainable Energy Reviews 2007;11(5):729–52.
[91] Mendes G, Ioakimidis C, Ferrao P. On the planning and analysis of integrated community energy systems: a review and survey of available tools. Renewable and Sustainable Energy Reviews 2011.
[92] Monfared M, Golestan S. Control strategies for single-phase grid integration of small-scale renewable energy sources: a review. Renewable and Sustainable Energy Reviews 2012;16(7):4982–93.
[93] Kjaer Soeren Baekhoej, Pedersen John K, Blaabjerg Frede. A review of single-phase grid-connected inverters for photovoltaic modules. IEEE Transactions on Industry Applications 2005;41(5):1292–306.
[94] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galvan E, Guisado RCP, Prats MaAM, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Transactions on Industrial Electronics 2006;53(4):1002–16.
[95] Dali M, Belhadj J, Roboam X. Hybrid solar–wind system with battery storage operating in grid-connected and standalone mode: control and energy management–experimental investigation. Energy 2010;35(6):2587–95.
[96] Shi L, Chew MYL. A review on sustainable design of renewable energy systems. Renewable and Sustainable Energy Reviews 2012;16(1):192–207.
[97] Zhou Z, Liu P, Li Z, Ni W. Economic assessment of a distributed energy system in a new residential area with existing grid coverage in China. Computers & Chemical Engineering, 2012.
[98] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power—a review of literature. Renewable and Sustainable Energy Reviews 2009;13:2041–50.
[99] Planas E, Gil-de-Muro A, Andreu J, Kortabarria I, Martínez de Alegría I. General aspects, hierarchical controls and droop methods in microgrids: a review. Renewable and Sustainable Energy Reviews 2013;17:147–59.
[100] Dallinger D, Wietschel M. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. Renewable & Sustainable Energy Reviews 2012;16(5):3370–82. http://dx.doi.org/10.1016/%20j.rser.2012.02.019.
[101] Guerrero JM, Vasquez JC, Matas J, Castilla M, de Vicuna LG. Control strategy for flexible microgrid based on parallel line-interactive UPS systems. IEEE Transactions on Industrial Electronics 2009;56(3):726–36.
[102] Jebaraj S, Iniyan S. A review of energy models. Renewable and Sustainable Energy Reviews 2006;10(4):281–311.
[103] Chen, YM, Cheng, CS, Wu, HC. 2006. Grid-connected hybrid PV/wind power generation system with improved DC bus voltage regulation strategy. In: Applied power electronics conference and exposition, APEC'06. Twenty-first annual IEEE; 2006. p. 7.
[104] Currie RAF, et al. Smarter ways to provide grid connections for renewable generators. Institute of Electrical and Electronic Engineers 2010.
[105] Coster EJ, Myrzik JMA, Kruimer B, Kling WL. Integration issues of distributed generation in distribution grids. Proceedings of the IEEE 2011;99(1):28–39.
[106] Purchala K, Belmans R, Exarchakos L, Hawkes AD. Distributed generation and the grid integration issues. London: K.U. Leuvenand, Imperial College; 2010. 〈http:/www.eusustel.be/public/documents_publ/WP/WP3/WP%203.4.1%20Distributed%20generation%20%20and%20grid%20integration%20issues.pdf〉. Available online.
[107] Alepuz S, Busquets-Monge S, Bordonau J, Gago J, González D, Balcells J. Interfacing renewable energy sources to the utility grid using a three-level inverter. IEEE Transactions on Industrial Electronics 2006;53(5):1504–11.
[108] Nehrir MH, Wang C, Strunz K, Aki H, Ramakumar R, Bing J, et al. A review of hybrid renewable/alternative energy systems for electric power generation: configurations, control, and applications. IEEE Transactions on Sustainable Energy 2011;2(4):392–403.
[109] Dincer I. Renewable energy and sustainable development: a crucial review. Renewable and Sustainable Energy Reviews 2000;4(2):157–75.
[110] Wolsink M. The research agenda on social acceptance of distributed generation in smart grids: renewable as common pool resources. Renewable and Sustainable Energy Reviews 2012;16(1):822–35.
[111] Ilskog E, Kjellström B. And then they lived sustainably ever after?-Assessment of rural electrification cases by means of indicators Energy Policy 2008;36(7):2674–84.
[112] Ilskog E, Kjellström B, Gullberg M, Katyega M, Chambala W. Electrification co-operatives bring new light to rural Tanzania. Energy Policy 2005;33:1299–307.
[113] Xin Huanhai, Qu Zhihua, Seuss J, Maknouninejad A. A self-organizing strategy for power flow control of photovoltaic generators in a distribution network. IEEE Transactions on Power Systems 2011:1462–73 Aug.
[114] Lads Ribeiro, et al. Making isolated renewable energy systems more reliable. Renewable Energy 2012;45(0):221–31.
[115] Schweizer-Ries P. Energy sustainable communities: environmental psychological investigations. Energy Policy 2008;36(11):4126 35.
[116] Pilkington B, Roach R, Perkins J. Relative benefits of technology and occupant behaviour in moving towards a more energy efficient, sustainable housing paradigm. Energy Policy 2011;39(9):4962–70.
[117] Shamsuzzoha A, Grant A, Clarke J. Implementation of renewable energy in Scottish rural area: a social study. Renewable and Sustainable Energy Reviews 2011.
[118] Rogers JC, et al. Public perceptions of opportunities for community-based renewable energy projects. Energy Policy 2008;36(11):4217–26.
[119] Geels FW, Schot J. Typology of sociotechnical transition pathways. Research Policy 2007;36:399–417.
[120] Roseland M. Sustainable community development: integrating environmental, economic, and social objectives. Progress in Planning 2000;54(2):73–132.
[121] Hansson SO. Technology and the notion of sustainability. Technology in Society 2010;32(4):274–9.

[122] Sinclair P. Describing the elephant: a framework for supporting sustainable development processes. Renewable and Sustainable Energy Reviews 2011;15 (6):2990–8.
[123] Bazmi AA, Zahedi G. Sustainable energy systems: role of optimization modeling techniques in power generation and supply—a review. Renewable and Sustainable Energy Reviews 2011;15(8):3480–500.
[124] Katti, PK; Khedkar, MK. Towards sustainable energy systems: integrating renewable energy sources is the key for rural area power supply. In: Power engineering conference; IPEC 2005. The seventh international; 2005. p. 1–104. IEEE.
[125] Hennicke P, Thomas S, Irrek W, Zymla B, Towards sustainable energy systems: integrating renewable energy and energy efficiency is the key. In: Discussion paper for the international conference 'Renewables'; 2004.
[126] Fullan M. Leadership & sustainability. Corwin: System thinkers in action; 2004.
[127] Sauma E, Jerardino S, Barria C, Marambio R, Brugman A, Mejía J. Electric-systems integration in the andes community: opportunities and threats. Energy Policy 2011;39(2):936–49.
[128] Ding JJ, Buckeridge JJ. Design considerations for a sustainable hybrid energy system, UNITECH Institute of Technology—Auckland Stand alone Power System—small wind system design guidelines. Australian Business Council for Sustainable Energy 2004(1): 7 June.
[129] Strauss, P, Kleinkauf, W, Reekers, J, Cramer, G, Betzios, G., Kythnos Island—19 years experience of renewable energy integration. In: Proceedings of renewable energies for Islands-towards 100% RES Supply 2001, Chania, Crete; 14–16 June 2001. ⟨http://insula.org/eurocaribbean/27_Strauss.pdf⟩.
[130] Basu AK, Chowdhury SP, Chowdhury S, Paul S. Microgrids: energy management by strategic deployment of DERs—a comprehensive survey. Renewable and Sustainable Energy Reviews 2011;15(9):4348–56.
[131] Praetorius B, Martiskainen M, Sauter R, Watson J. Technological innovation systems for microgeneration in the UK and Germany–a functional analysis. Technology Analysis & Strategic Management 2010;22(6):745–64.
[132] Lidula NWA, Rajapakse AD. Microgrids research: a review of experimental microgrids and test systems. Renewable and Sustainable Energy Reviews 2011;15(1):186–202.
[133] Jacobsson S, Bergek A. Innovation system analyses and sustainability transitions: contributions and suggestions for research. Environmental Innovation and Societal Transitions 2011;1(1):41–57.
[134] Jimeno J, Anduaga J, Oyarzabal J, de Muro A. Architecture of a microgrid energy management system. European Transactions on Electrical Power 2011;21(2):1142–58;
[7] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrids management. IEEE Power and Energy Magazine 2011;9(5):54–65.
[135] Ilic M. Dynamic monitoring and decision systems for enabling sustainable energy services. Proceedings of the IEEE 2011;99(1):58e79.
[136] Brown, RE.; Impact of smart grid on distribution system design; power and energy society general meeting—conversion and delivery of electrical energy in the 21st century, IEEE, 20–24 July 2008; p. 1–4.
[137] Metke A, Ekl R. Security technology for smart grid networks. IEEE Transactions on Smart Grid 2010;1(1):99e107.
[138] Glicksman LR, Taub S. Thermal and behavioral modeling of occupant-controlled heating, ventilating and air conditioning systems. Energy and Buildings 1997;25(3):243–9.
[139] Mohsenian-Rad AH, Leon-Garcia A. Optimal residential load control with price prediction in real-time electricity pricing environments. IEEE Transactions on Smart Grid 2010;1(2):120–33.
[140] Colet-Subirachs A , A Ruiz-Alvarez , O Gomis-Bellmunt , F Alvarez-Cuevas-Figuerola A Sudria-Andreu. Control of a utility connected microgrid. In: Proc. IEEE PES Innov. smart grid technol. conf. Eur. (ISGT Eur.); 2010. p.1–7.
[141] Vyatkin V, Zhabelova G, Higgins N, Schwarz K, Nair N-KC. Towards intelligent smart grid devices with IEC 61850 interoperability and IEC 61499 open control architecture.In: Proc. IEEE PES Transm. Distrib. Conf. Expo. 2010 NIST framework and roadmap for smart grid interoperability standards; 2010. P 1–8.
[142] Panapakidis IP, Sarafianos DN, Alexiadis MC. Comparative analysis of different grid-independent hybrid power generation systems for a residential load. Renewable and Sustainable Energy Reviews 2012;16(1):551–63.
[143] Zeng Z, Yang H, Zhao R. Study on small signal stability of microgrids: a review and a new approach. Renewable and Sustainable Energy Reviews 2011;15 (9):4818–28.
[144] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrids management. IEEE Power and Energy Magazine 2008;6(3):54–65.
[145] Outhred H. The smart grid, getting the incentives right. National Smartgrids Summit; 2008.
[146] Caron, S, Kesidis, G. . Incentive-based energy consumption scheduling algorithms for the smart grid. In: Smart grid communications (SmartGridComm), 2010 First IEEE international conference on; 2010. p. 391–396.
[147] Ustun TS, Ozansoy C, Zayegh A. Recent developments in microgrids and example cases around the world—a review. Renewable and Sustainable Energy Reviews 2011;15(8):4030–41.
[148] Snape JR, Irvine KN, Rynikiewicz C. Understanding energy behaviours and transitions through the lens of a smart grid agent based model. European Council for an Energy Efficient Economy 2011.
[149] O'Brien G, Hope A. Localism and energy: negotiating approaches to embedding resilience in energy systems. Energy Policy 2010;38(12):7550–8.
[150] Moore DR. The client perspective on factors in the retrofitting of sustainable technologies to traditional rural homes in North East Scotland. Journal of Building Appraisal 2010;6(2):117–28.
[151] Ciegis R, Ramanauskiene J, Martinkus B. The concept of sustainable development and its use for sustainability scenarios. Inzinerine Ekonomika-Engineering Economics 2009;2(62):28–37.
[152] Rae C, Bradley F. Energy autonomy in sustainable communities—a review of key issues. Renewable and Sustainable Energy Reviews 2012;16 (9):6497–506.
[153] Walker G, Hunter S, Devine-Wright P, Evans B, Fay H. Harnessing community energies: explaining and evaluating community-based localism in renewable energy policy in the UK. Global Environmental Politics 2007;7(2):64–82.
[154] Abu-Sharkh S, Arnold RJ, Kohler J, Li R, Markvart T, Ross JN, et al. Can microgrids make a major contribution to UK energy supply? Renewable and Sustainable Energy Reviews 2006;10(2):78–127.
[155] Barton H. Sustainable communities: the potential for eco-neighbourhoods. Routledge; 2000.
[156] Afgan NH, Carvalho MG. Sustainability assessment of a hybrid energy system. Energy Policy 2008;36(8):2903–10.
[157] Afzal A, Mohibullah M, Kumar Sharma V. Optimal hybrid renewable energy systems for energy security: a comparative study. International Journal of Sustainable Energy 2010;29(1):48–58.
[158] Balijepalli VM, Khaparde SA. Smart and sustainable energy systems for developing countries: an Indian perspective. In: Power and energy society general meeting; 2011. p. 1–8. IEEE.
[159] Dounis AI, Caraiscos C. Advanced control systems engineering for energy and comfort management in a building environment—a review. Renewable and Sustainable Energy Reviews 2009;13(6):1246–61.
[160] Livengood D, Larson R. The energy box: locally automated optimal control of residential electricity usage. Service Science 2009;1(1):1–16.
[161] Metke A, Ekl R. Security technology for smart grid networks. IEEE Transactions on Smart Grid 2010;1(1):99e107.
[162] Amin SM, Wollenberg BF. Toward a smart grid: power delivery for the 21st century. IEEE Power and Energy Magazine 2005;3(5):34–41.
[163] Amin M. Toward self-healing energy infrastructure systems (cover feature). IEEE Computer Applications in Power 2001;14(1):20–8.
[164] Amin M, Schewe PF. Preventing blackouts. Scientific American; 60–7.
[165] Piagi, P, Lasseter, RH. Autonomous control of microgrids. In: Power engineering society general meeting; 2006. IEEE p. 8, IEEE.
[166] Amin M. Challenges in reliability, security, efficiency, and resilience of energy infrastructure: toward smart self-healing electric power grid, power and energy society general meeting—conversion and delivery of electrical energy in the 21st century, 20–24 July 2008; 2008. IEEE, p 1–5.
[167] Amin M. North America's electricity infrastructure: are we ready for more perfect storms? IEEE Security and Privacy Magazine 2003;1(5):19–25 Sept./October.
[168] Lasseter RH, Paigi P. Microgrid: a conceptual solution. In: Power electronics specialists conference, 2004. PESC 04. 2004 IEEE 35th annual. IEEE; 2004. p 4285–90.
[169] Lasseter, RH, Akhil, A Marnay, C Stephens, J Dagle, J Guttromson, R et al. The CERTS microgrid concept, white paper for transmission reliability program, office of power technologies, US Department of Energy; 2002
[170] Lasseter RH. Microgrids. In: Power engineering society winter meeting; 2002. IEEE vol. 1, p. 305–8.
[171] Del Carpio Huayllas TE,Ramos DS, Vasquez-Arnez RL. Microgrid systems: current status and challenges, transmission and distribution conference and exposition: Latin America (T&D-LA); 2010. IEEE/PES, p 7–12.
[172] O'Neill-Carrillo E, Irizarry-Rivera AA, Colucci-Rios JA, Perez-Lugo M, Ortiz-Garcia C. Sustainable energy: Balancing the economic, environmental and social dimensions of Energy. In: Energy 2030 conference, ENERGY 2008; 2008a. p. 1–7. IEEE.
[173] O'Neill-Carrillo E, Frey W, Ortiz-Garcia C, Irizarry-Rivera AA, Perez-Lugo M, Colucci-Rios JA. Advancing a sustainable energy ethics through stakeholder engagement. In: Energy 2030 conference, Energy IEEE; 2008. p. 1–6. IEEE.
[174] Omer AM. Energy, environment and sustainable development. Renewable and Sustainable Energy Reviews 2008;12(9):2265–300.
[175] LAdS Ribeiro, et al. Making isolated renewable energy systems more reliable. Renewable Energy 2012;45(0):221–31.
[176] Schweppe FC, Tabors RD, Kirtley JL Jr., Law SR, Levy PF, Outhred H, et al., Homeostatic control of power systems. In: Fourth energy monitoring and control system conference, Norfolk, VA; November 1979.
[177] MIT Energy Laboratory; MIT Homeostatic Control Study Group, New electric utility management and control systems. In: Proceedings of conference, held in Boxborough, MA, MIT Energy Laboratory; May 30–June 1 1979.
[178] Schweppe FC, Tabors RD, Kirtley Jr., JL, Outhred H, Pickel FH, Cox AJ. Homeostatic utility control. In: IEEE transactions on power apparatus and systems, PAS-99, No. 3, 1151-1163; May/June 1980.
[179] Sterling TL, Williams RD, Kirtley Jr., JL. Control and monitoring system communications for effective energy use. In: IEEE Power Engineering Society 1981 summer meeting, Portland, OR; July 1981. paper no. 81 SM 307-8.
[180] Schweppe FC, Tabors RD, Kirtley Jr. JL. Homeostatic control for electric power usage. IEEE Spectrum 1982;44–48.
[181] Tabors RD, Schweppe FC, Kirtley Jr, JL. Homeostatic control: the utility/customer marketplace for electric power. In: Proc. local heat and power generation: a new opportunity for British Industry, Inderscience Enterprises, ; 1983, p 66-88, St. Helier, Jersey, UK.
[182] Ramchurn S, Vytelingum P, Rogers A, Jennings N. Agent-based homeostatic control for green energy in the smart grid. ACM Transactions on Intelligent Systems and Technology 2011;2(4) article 35.

[183] Morganti G, Perdon A, Conte G, Scaradozzi D. Multi-agent system theory for modelling a home automation system. Bio-Inspired Systems: Computational and Ambient Intelligence 2009:585–93.
[184] Miller S. Multi-agent based techniques for coordinating the distribution of electricity in a microgrid environment; 2010.
[185] Dobbyn J, Thomas G. Seeing the light: the impact of microgeneration on the way we use energy. Qualitative research findings. Hub Research Consultants, London, on behalf of the Sustainable Consumption Roundtable DTI, Our energy challenge: securing clean, affordable energy for the long term. Department of Trade and Industry, London; 2006.
[186] Markvart T. Sizing of hybrid photovoltaic–wind energy systems: solar energy. IEEE Transactions on Energy Conversion 1998;57:277–81.
[187] Chedid R, Rahman S. Unit sizing and control of hybrid wind–solar power systems. IEEE Transactions on Energy Conversion 1997;12(1):79–85.
[188] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Applied Energy 2010;87(2):380–9.
[189] Engin M. Sizing and simulation of PV-wind hybrid power system. International Journal of Photoenergy 2013.
[190] Alanne K, Saari A. Distributed energy generation and sustainable development. Renewable & Sustainable Energy Reviews 2006;10(6):539–58.
[191] Yuanxiong G, Miao P, Yuguang F. Optimal power management of residential customers in the smart grid. IEEE Transactions on Parallel and Distributed Systems 2012;23(9):1593–606. http://dx.doi.org/10.1109/TPDS.2012.25.
[192] Black JW, Larson RC. Strategies to overcome network congestion in infrastructure systems. Journal of Industrial and Systems Engineering 2007;1:97–115.
[193] Darby S. Making it obvious: designing feedback into energy consumption. In: Proceedings of 2nd international conference on energy efficiency in household appliances and lighting. Italian Association of Energy Economists/EC-SAVE programme; 2001.
[194] Darby S. The effectiveness of feedback on energy consumption. In: A review for DEFRA of the literature on metering, billing and firect displays 2006:486.
[195] Darby S. Social learning and public policy: lessons from an energy-conscious village. Energy Policy 2006;34(17):2929–40.
[196] De Young R. Changing behaviour and making it stick: the conceptualistion and management of conservation behaviour. Environment and Behaviour 1993;25(4):485–505.
[197] Fischer C. Feedback on household electricity consumption: a tool for saving energy? Energy Efficiency 2008;1(1):79–104.
[198] Khan, MS. Supervisory hybrid control of a micro grid system. In: Electrical power conference, EPC 2007, IEEE Canada; 25–26 Oct. 2007.
[199] King DE. Electric power micro-grids: opportunities and challenges for an emerging distributed energy architecture. Doctoral dissertation. Carnegie Mellon University; 2006.
[200] Brokish KM. Adaptive load control of microgrids with non-dispatchable generation. PhD diss.. Massachusetts Institute of Technology; 2009.
[201] Walker G, Devine-Wright P. Community renewable energy: what should it mean? Energy Policy 2008;36(2):497–500.
[202] Schweizer-Ries P. Energy sustainable communities: environmental psychological investigations. Energy Policy 2008;36(11):4126 35.
[203] Pilkington B, Roach R, Perkins J. Relative benefits of technology and occupant behaviour in moving towards a more energy efficient, sustainable housing paradigm. Energy Policy 2011;39(9):4962–70.
[204] Rogers JC, et al. Public perceptions of opportunities for community-based renewable energy projects. Energy Policy 2008;36(11):4217–26.
[205] Shamsuzzoha A, Grant A, Clarke J. Implementation of renewable energy in Scottish rural area: a social study. Renewable and Sustainable Energy Reviews 2011.
[206] Dallinger D, Wietschel M. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. Renewable & Sustainable Energy Reviews 2012;16(5):3370–82. http://dx.doi.org/10.1016/j.rser.2012.02.019.
[207] Bhave AG. Hybrid solar–wind domestic power generating system—case study. Renewable Energy 1999;17(3):355–8.
[208] Wei Z, Liu J, Zhu G, HE X, Gong W. Power system vulnerability. Electric Power Automation Equipment 2009;7:007.
[209] Yu X, Singh C. A practical approach for integrated power system vulnerability analysis with protection failures. IEEE Transactions on Power Systems 2004;19(4):1811–20.
[210] Fouad AA, Zhou Q, Vittal V. System vulnerability as a concept to assess power system dynamic security. IEEE Transactions on Power Systems 1994;9(2):1009–15.
[211] Adachi T, Ellingwood BR. Serviceability of earthquake-damaged water systems: effects of electrical power availability and power backup systems on system vulnerability. Reliability Engineering & System Safety 2008;93(1):78–88.
[212] Goodman M, Karash R, Lannon C, O'Reilly KW, Seville D. Designing a systems thinking intervention. Waltham, MA: Pegasus Communications, Inc.; 1997.
[213] O'Connor J. The art of systems thinking: essential skills for creativity and problem solving. London: Thorsons, An Imprint of HarperCollins Publishers; 1997.
[214] Espejo R. What is systemic thinking? System Dynamics Review 2006;10(2–3):199–212.
[215] Meadows Donella H. Thinking in systems: a primer. Sustainability Institute's Diana Wright; 2008.
[216] Bak P, Tang C, Weisenfeld K. Self-organized criticality. Physical Review A: Atomic, Molecular, and Optical Physics 1988;38:364–74.
[217] Von Bertalanffy L. General system theory. Revised ed. New York: George Braziller; 1973.
[218] Nicolis G, Prigogine I. Self-organization in non-equilibrium systems. New York: Wiley; 1977.
[219] Von Foerster H. On self-organising systems and their environments. In: Yovits MC, Cameron S, editors. Self-organising systems. London: Pergamon Press; 1960. p. 30–50.
[220] Von Foerster H, Zopf G, editors. Principles of self-organization. New York: Pergamon; 1962.
[221] Von Foerster H. Observing systems: selected papers of Heinz von Foerster. Seaside, CA: Intersystems; 1981.
[222] Von Foerster H. Cybernetics of cybernetics. 2nd ed. Minneapolis: Future Systems; 1996.
[223] Wiener N. Cybernetics. American Journal of Physics 1949;17:226–7.
[224] Beer S. Cybernetics and management. English University Press; 214.
[225] Gleick James. Chaos: making a new science. London: Sphere Books Ltd; 1987.
[226] Kellert SH. In the wake of chaos: unpredictable order in dynamical systems. University of Chicago Press; 0-226-42976-832.
[227] Miller JH, p. Scott E. Complex adaptive systems: an introduction to computational models of social life. Princeton and Oxford: Princeton University Press; 2007 Princeton and Oxford: Princeton University Press; 2007.
[228] Branlat, M Woods, DD. How do systems manage their adaptive capacity to successfully handle disruptions? A resilience engineering perspective, complex adaptive systems—resilience, robustness, and evolvability: Papers from the Association for the Advancement of Artificial Intelligence (⟨www.aaai.org⟩). In: AAAI Fall symposium; 2010. FS-10-03.
[229] Holland JH. Hidden order: how adaptation builds complexity. Addison-Wesley; 1996.
[230] Rammel C, Stagl S, Wilfing H. Managing complex adaptive systems—a co-evolutionary perspective on natural resource management‖. Ecological Economics 2007;63(1):9–21 15 June.
[231] U.S. Department of Energy site information; 2010 ⟨http:/energy.gov/oe/technology-development/smart-grid⟩ (accessed on 19 April, 2013).
[232] Lotka AJ. Contribution to the energetics of evolution. Proceedings of the National Academy of Sciences 1922;8:147–51.
[233] Del Sol F, Sauma E. Economic impacts of installing solar power plants in northern Chile. Renewable & Sustainable Energy Reviews 2013;19:489–98.
[234] Munoz F, Sauma E, Hobbs B. Approximations in power transmission planning: implications for the cost and performance of renewable portfolio standards. Journal of Regulatory Economics 2013;43(3):305–38.
[235] Sauma E. The impact of transmission constraints on the emissions leakage under Cap-and-Trade Program. Energy Policy 2012;51:164–71.
[236] Sauma E. Valuation of the economic impact of the initial allocation of tradable emission permits in air pollution control. Journal of Energy Engineering—ASCE 2011;137(1):11–20.
[237] Sauma E. Inter-temporal planning of transmission expansions in restructured electricity markets. Journal of Energy Engineering—ASCE 2009;135(3):73–82.
[238] Sauma E, Oren S. Do generation firms in restructured electricity markets have incentives to support social-welfare-improving transmission investments? Energy Economics 2009;31(5):676–89.
[239] Sauma E, Oren S. Economic criteria for planning transmission investment in restructured electricity markets. IEEE Transactions on Power Systems 2007;22(4):1394–405.
[240] Sauma E, Oren S. Proactive planning and valuation of transmission investments in restructured electricity markets. Journal of Regulatory Economics 2006;30(3):261–90.
[241] Pozo D, Contreras J, Sauma E. If you build it, he will come: anticipative power transmission planning. Energy Economics, March 2013;36:135–46.
[242] Pozo D, Sauma E, Contreras J. A three-level static MILP model for generation and transmission expansion planning. IEEE Transactions on Power Systems, February 2013;28(1):202–10.
[243] Norero J, Sauma E. Ex-ante assessment of the implementation of an energy efficiency certificate scheme in Chile. Journal of Energy Engineering—ASCE, 138; 63–72.